Weak Lensing with Current and Future Surveys

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CCAPP

Outline

1. Weak lensing and cosmology basics
2. Cluster weak lensing measurements
3. Blending
4. Looking to the future
5. Summary

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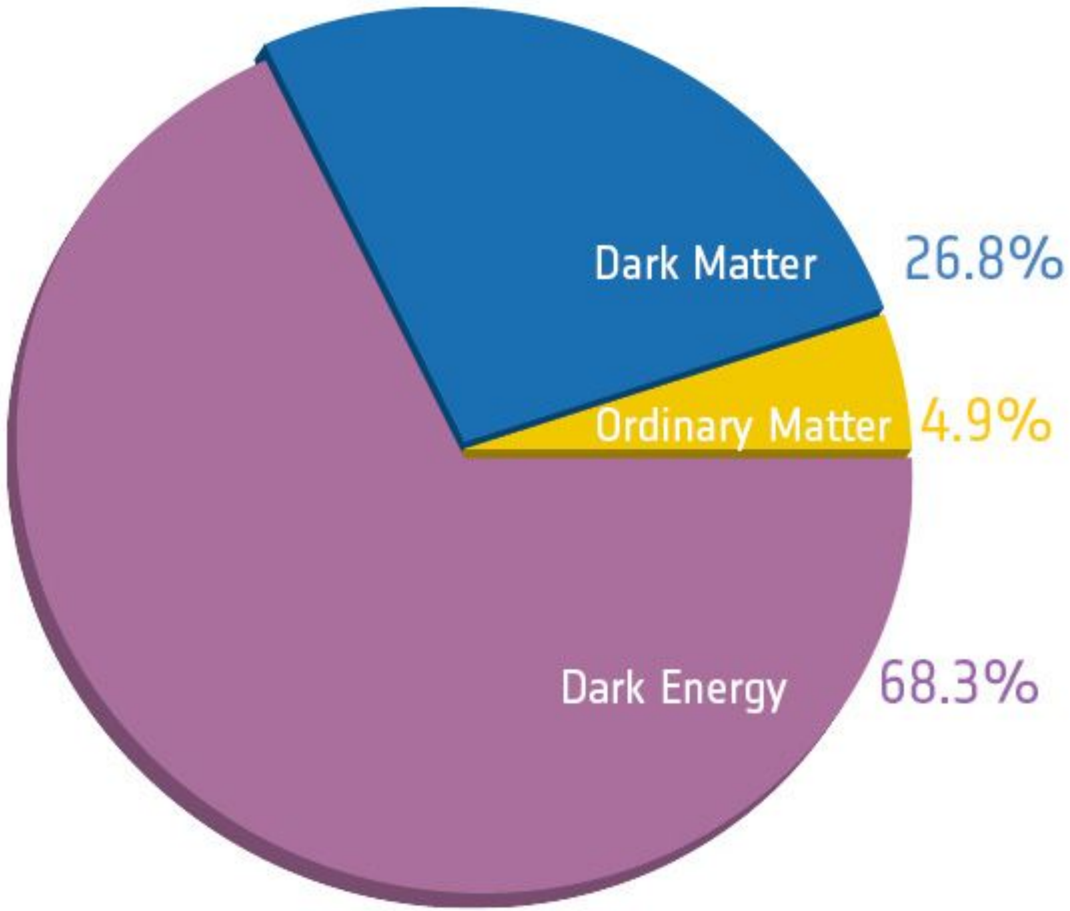
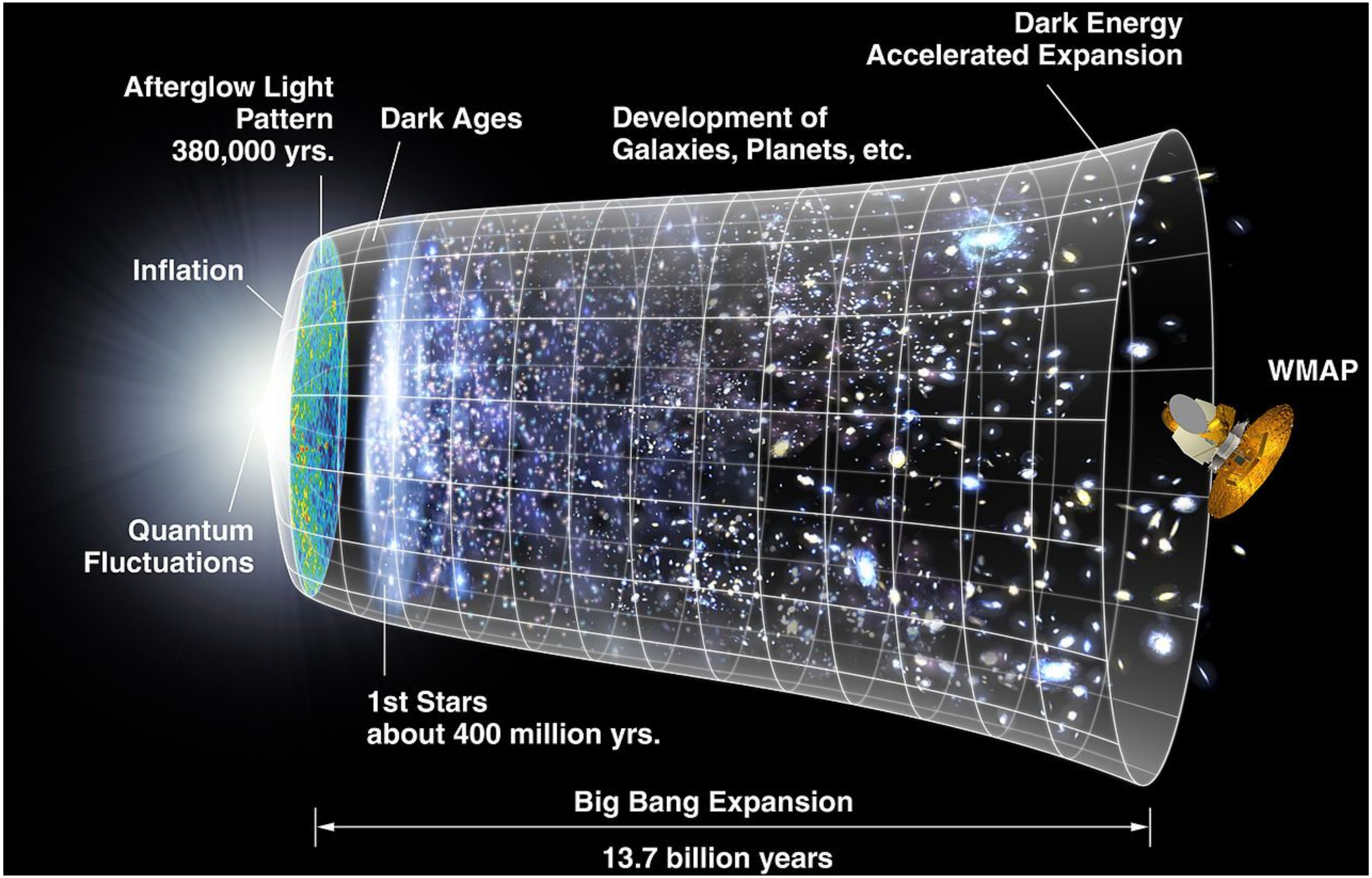
Cosmology 101



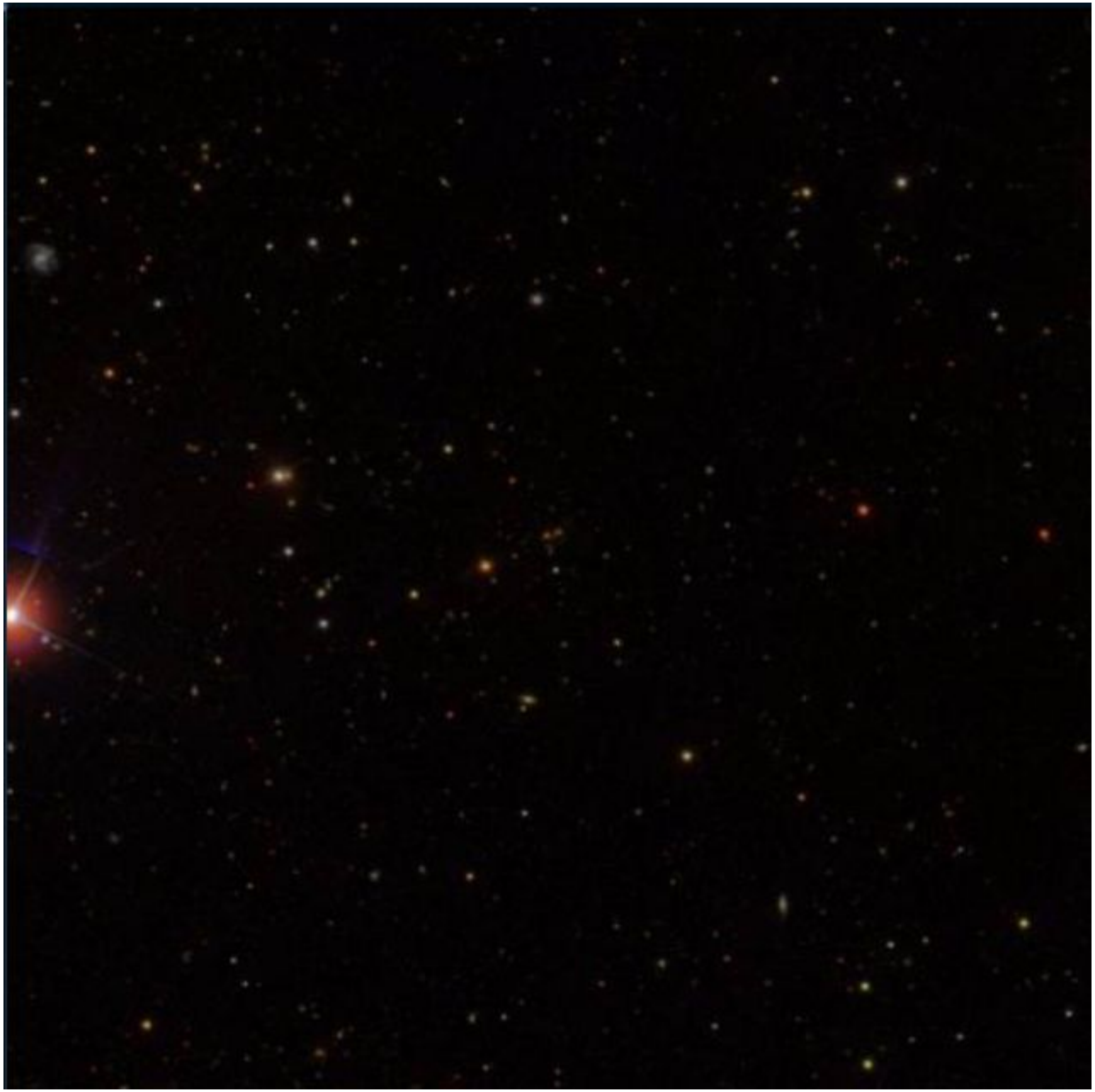
We can't see
most of
what makes up
the universe

Cosmology 101



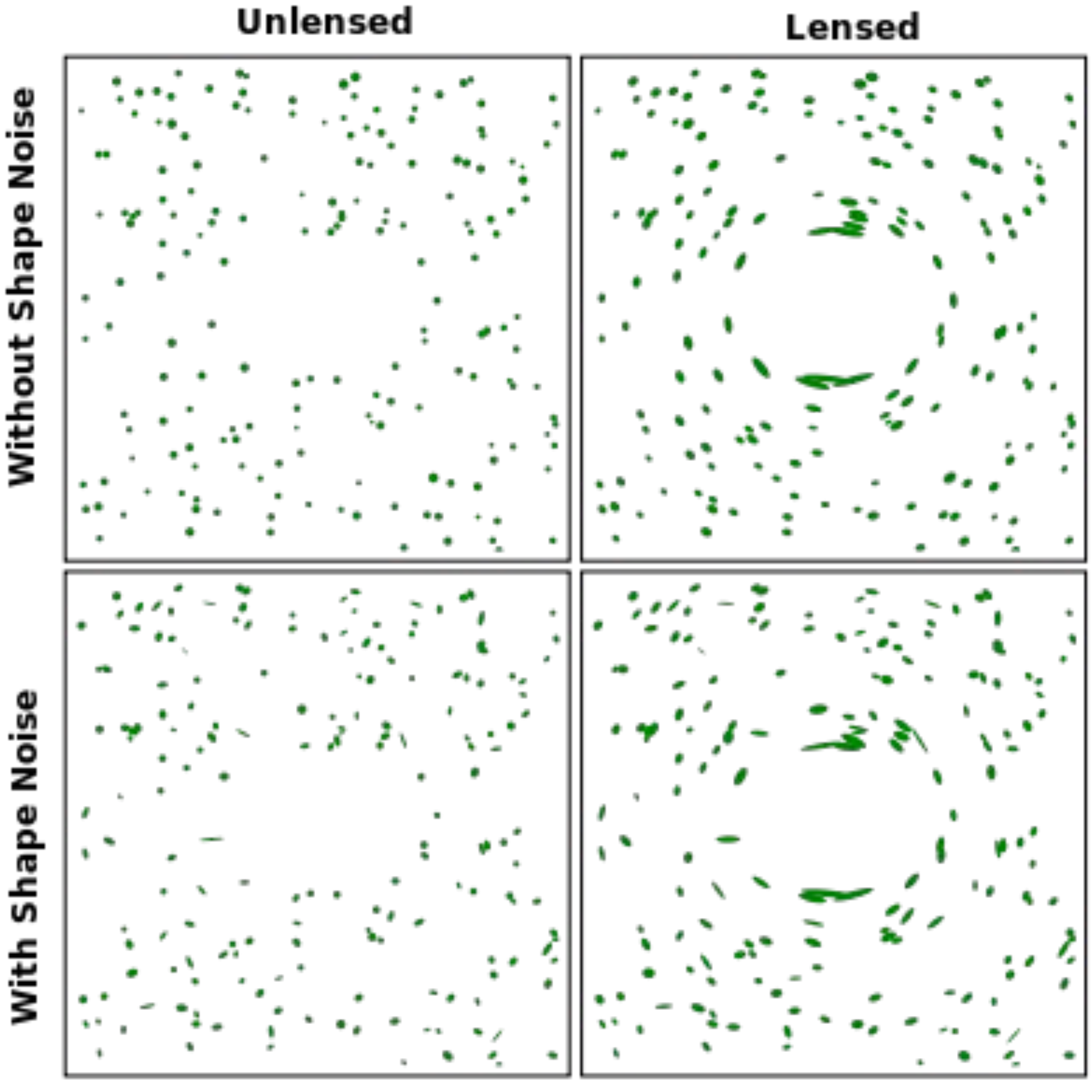
NASA/WMAP science team

Judy Schmidt; NASA/ESA



SDSS

Weak lensing basics



Wikipedia (J. Bosch)

In the thin-lens (linear) limit, lensing is sensitive to a scaled surface mass density:

$$\kappa(\mathbf{R}) = \frac{\Sigma(\mathbf{R})}{\frac{c^2}{4\pi G}\frac{D_A(z_{\rm source})}{D_A(z_{\rm lens})D_A(z_{\rm lens}, z_{\rm source})}}$$

For extended objects, lensing leads to a distortion called a shear, γ, which we measure using ellipticities *e*.

$$\langle\gamma_t(R)\rangle = \bar{\kappa}(< R) - \langle\kappa(R)\rangle$$

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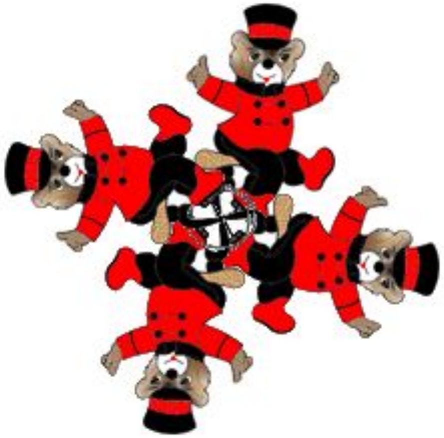
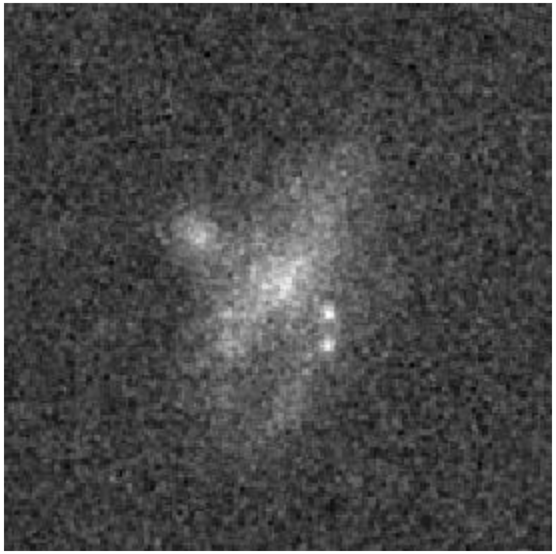
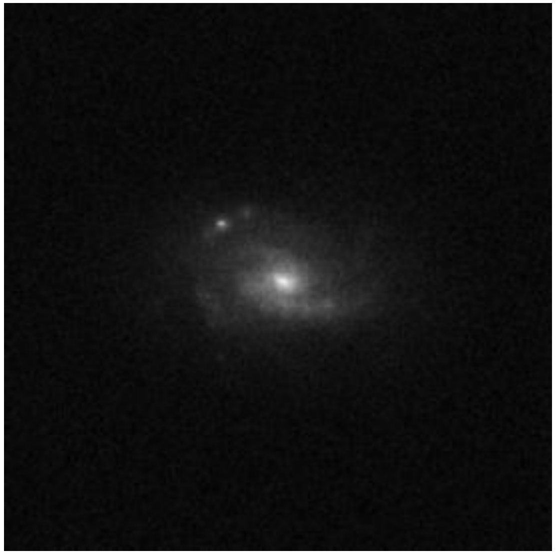
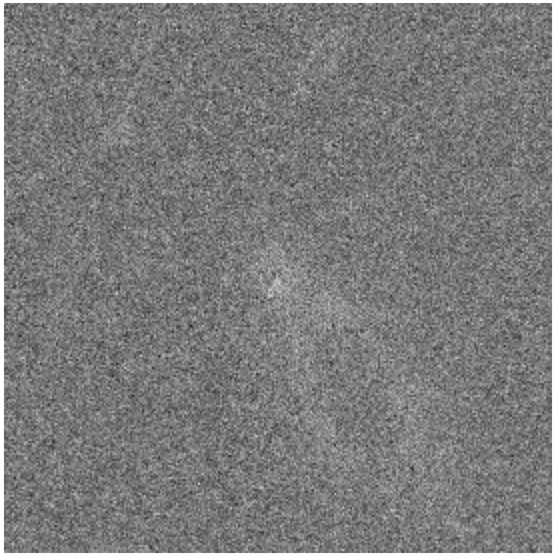
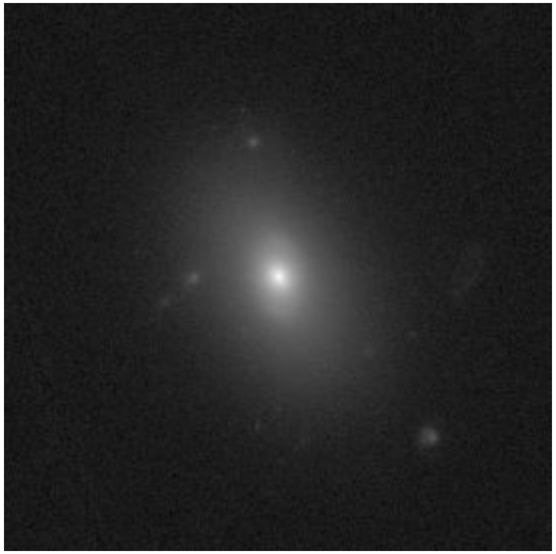
$$\langle\gamma_t(R)\rangle = \bar{\kappa}(< R) - \langle\kappa(R)\rangle$$

Note: by galaxy ***shapes*** I don't mean galaxy ***morphology.***

This is round: 

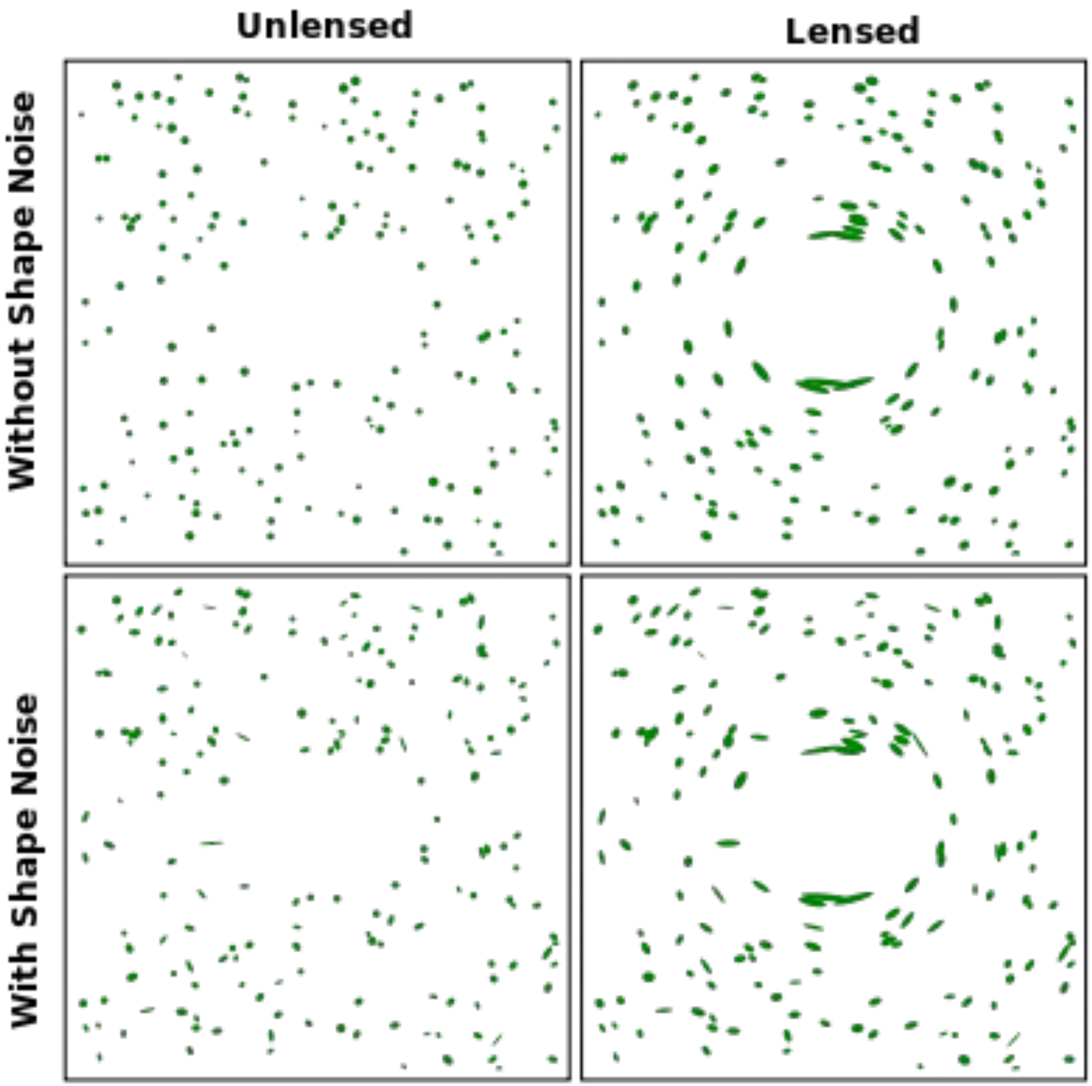





Note: this is just gravity--from *all* matter sources.

$$\kappa(\mathbf{R}) = \frac{\Sigma(\mathbf{R})}{\frac{c^2}{4\pi G}\frac{D_A(z_{\rm source})}{D_A(z_{\rm lens})D_A(z_{\rm lens}, z_{\rm source})}}$$

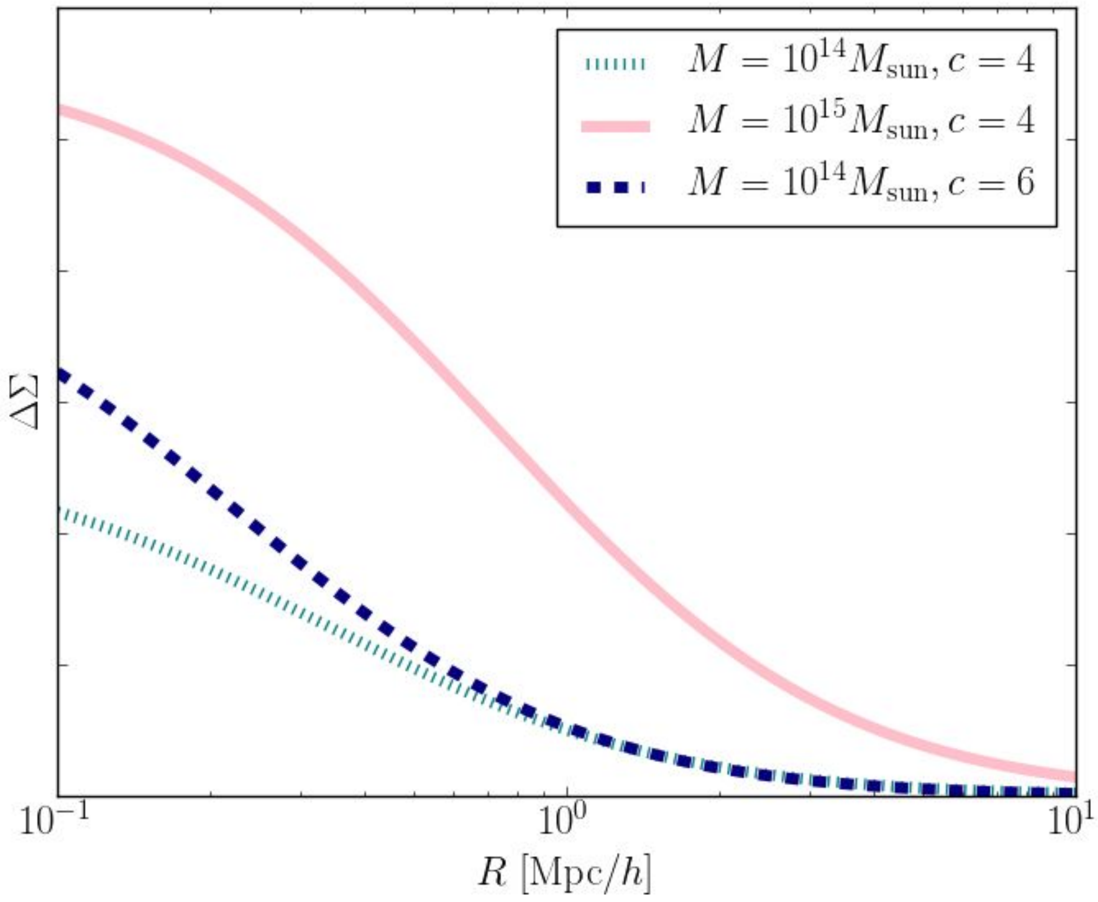
And other cosmological parameters are encoded in those angular diameter distances, so we're sensitive to those, too!

Weak lensing basics



Wikipedia (J. Bosch)

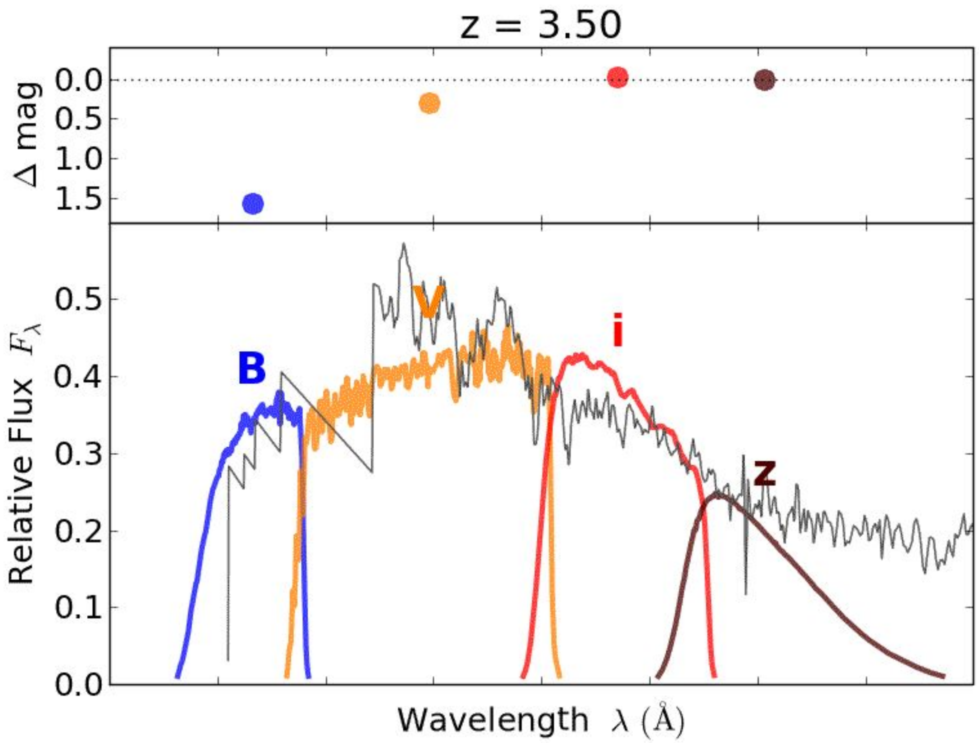
Lensing signals



Different Navarro, Frenk & White (NFW; 1996) profiles, a typical assumption for the density distribution of dark matter haloes derived from simulations.

Photometric redshifts

With millions of objects, we can't get a spectroscopic redshift for every galaxy. Instead we use photometric redshifts (or photo-*z*s).



Dan Coe, http://www.stsci.edu/~dcoe/BPZ/intro.html

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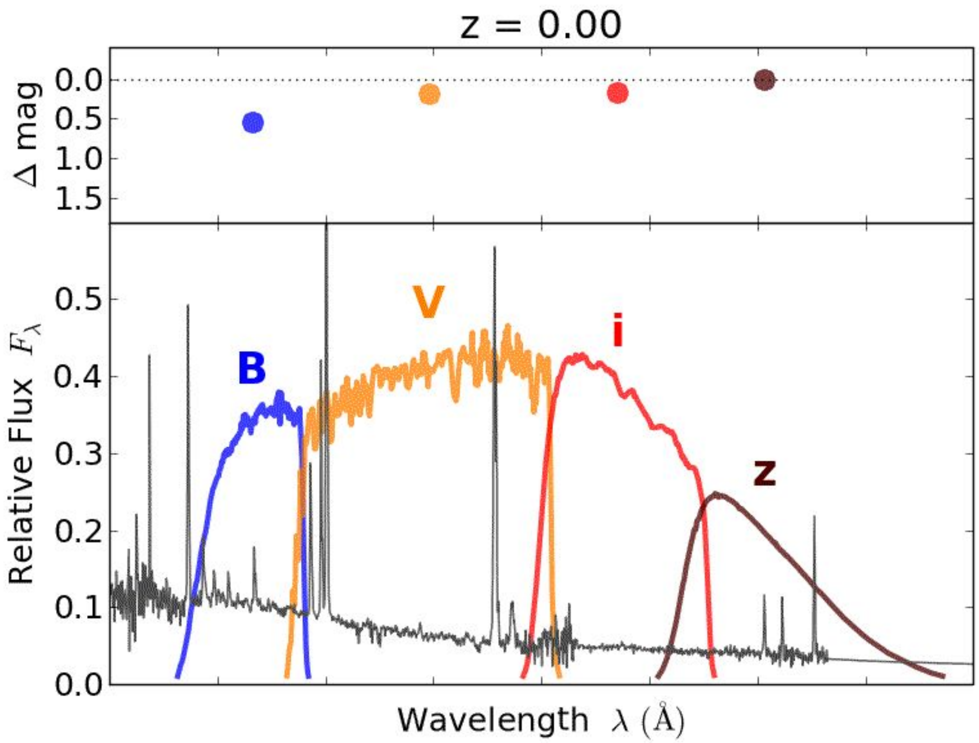
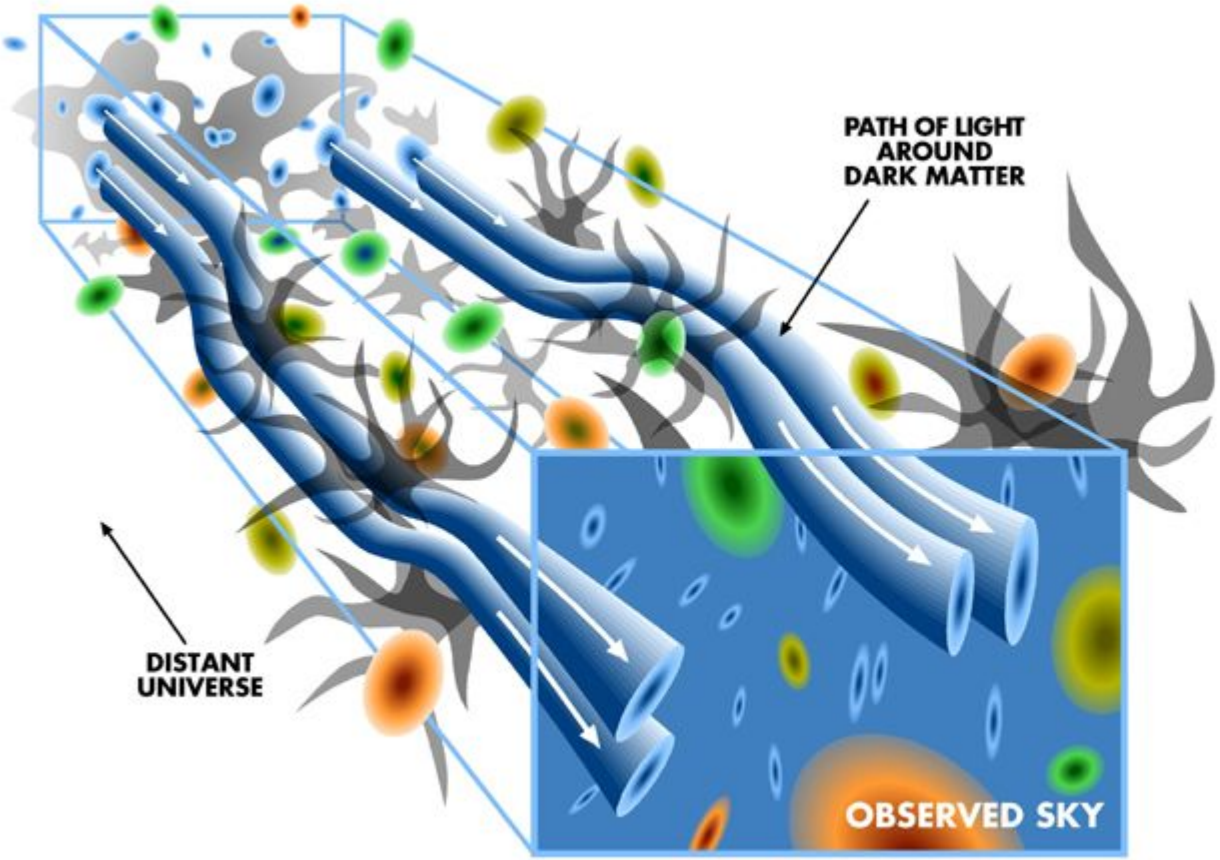


Dan Coe, http://www.stsci.edu/~dcoe/BPZ/intro.html

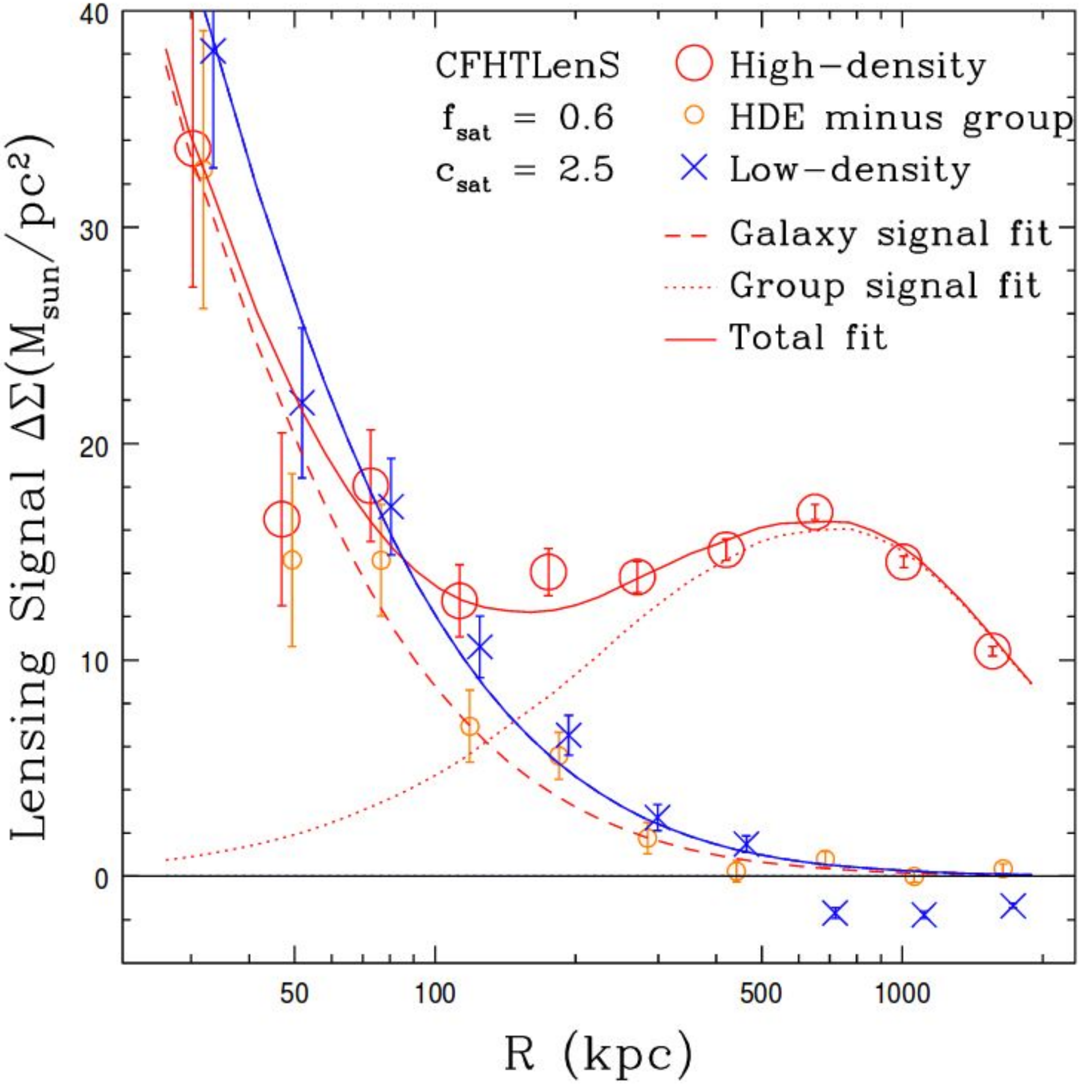
What can you do with weak lensing?

Cosmic shear



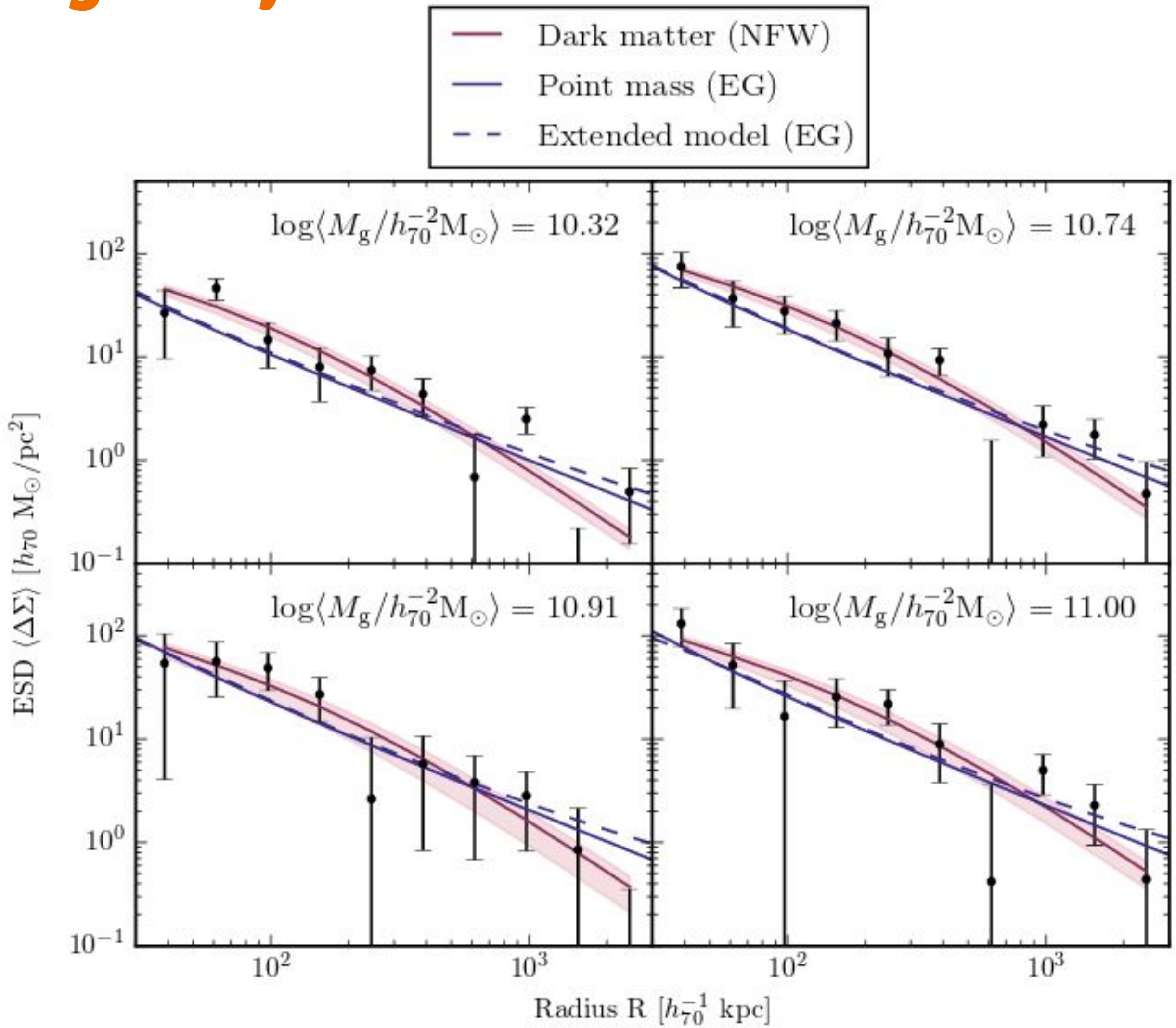
LSST collaboration

Galaxy-galaxy lensing



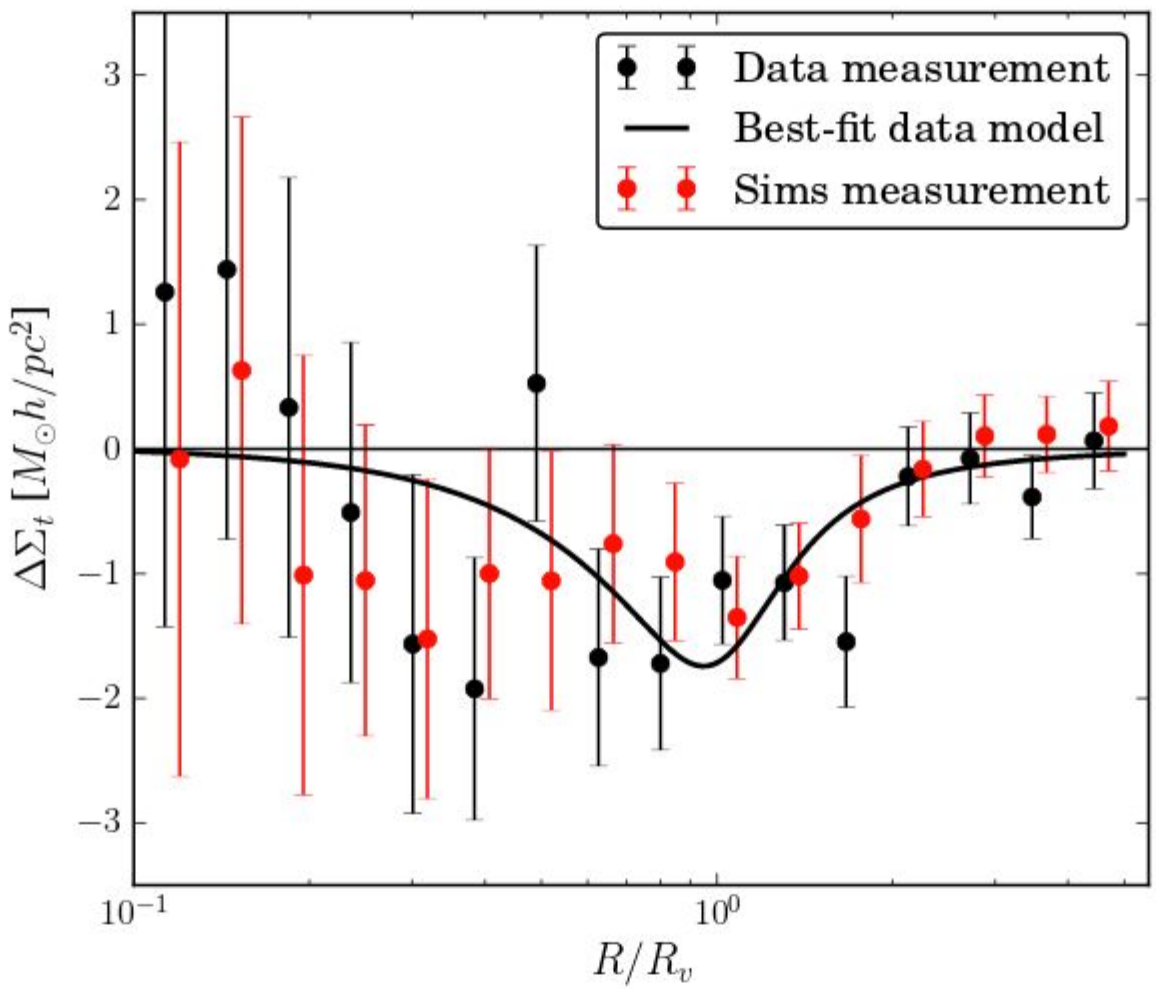
Brouwer et al. 2016 (KiDS)

Modified gravity



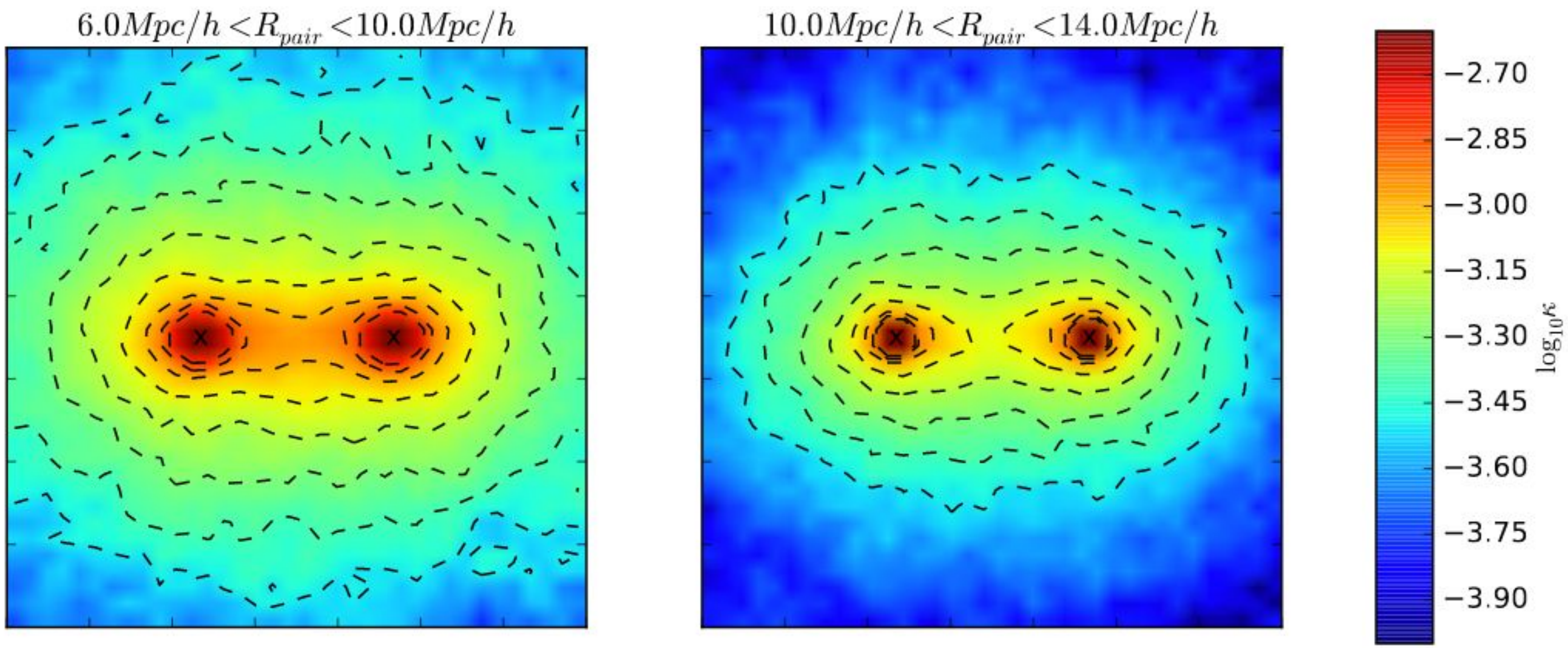
Brouwer et al. 2017 (KiDS)

Lensing by voids



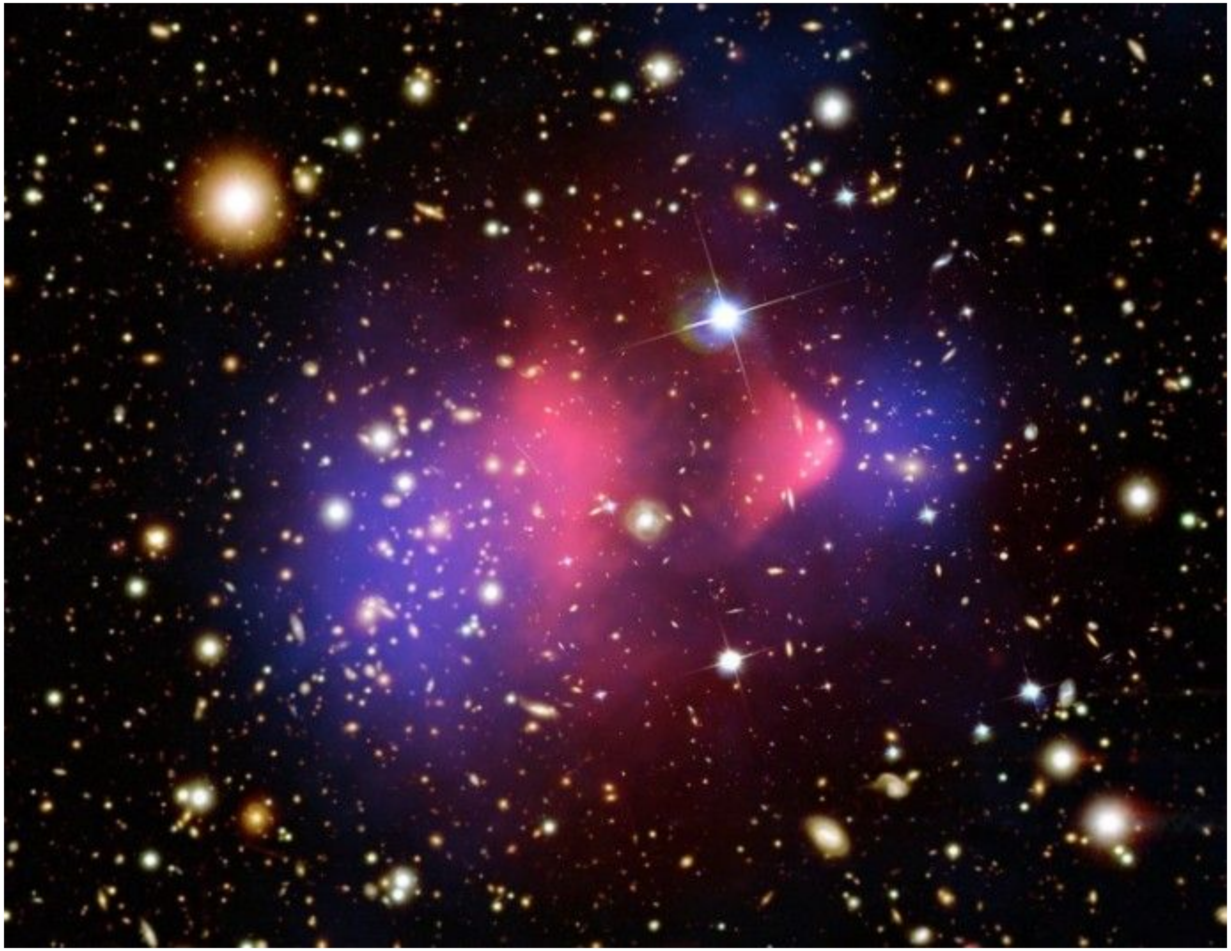
Sánchez et al. 2017 (DES)

Lensing by filaments



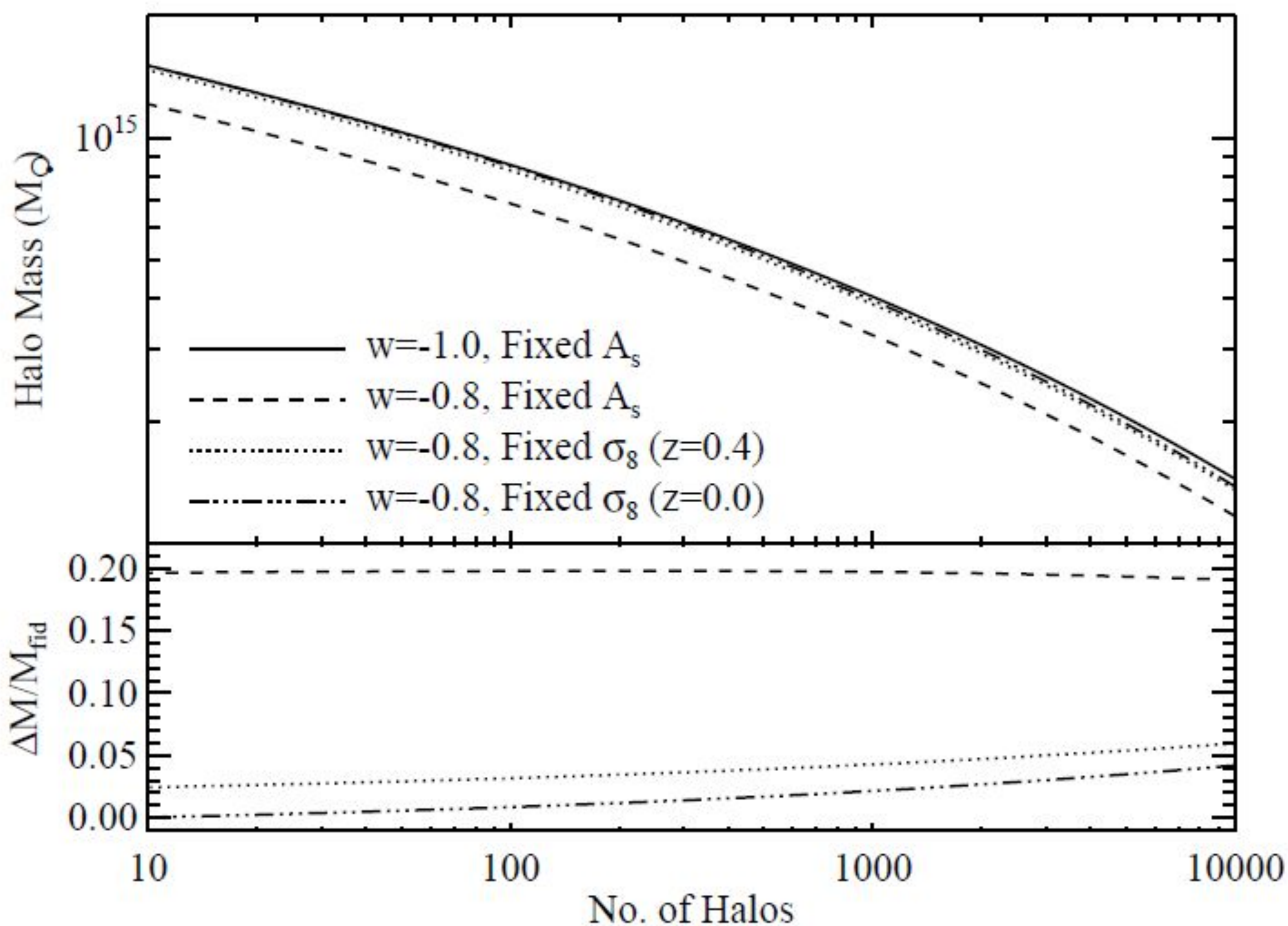
Clampitt et al. 2014 (SDSS)

Galaxy cluster lensing



X-ray: Markevitch et al.; lensing and optical: Clowe et al.

(Why galaxy cluster lensing?)



Weinberg et al. 2012

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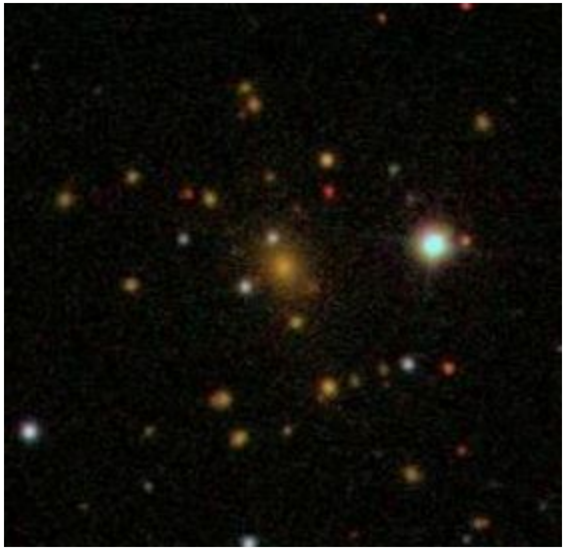
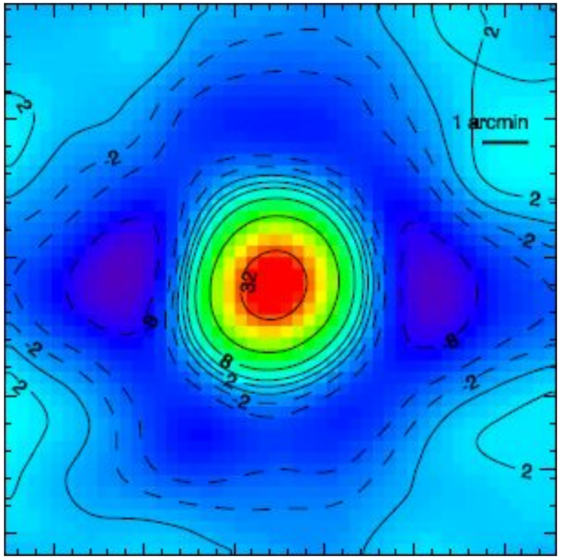
Galaxy cluster basics

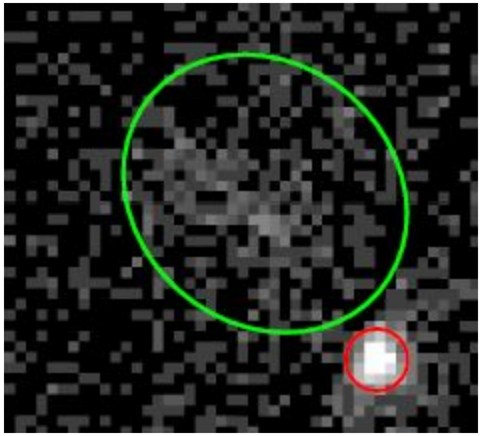


Optical

CMB



X-ray



Data sets

RBC X-ray clusters (subset of the MCXC, Piffaretti et al. 2011):

- $0.04<z<0.4$
- 166 clusters in shape catalogue area
- Mass proxy is L_x

redMaPPer optical clusters (Rykoff et al 2014, Rozo et al 2015):

- $0.1<z<0.33$
- $20<\lambda<140$ (for reasons to be explained later)
- 5570 clusters in shape catalogue area

Data sets

Weak lensing data (Reyes et al 2012, Nakajima et al 2012):

- 39 million galaxies in SDSS DR8 (1.2/arcmin^2)
- Regaussianization shapes
- Photo-zs from ZEBRA
    - Using a set of empirical templates and extra templates interpolated between pairs of the empirical templates
    - Starburst galaxies had bad fits and are excluded from this data set

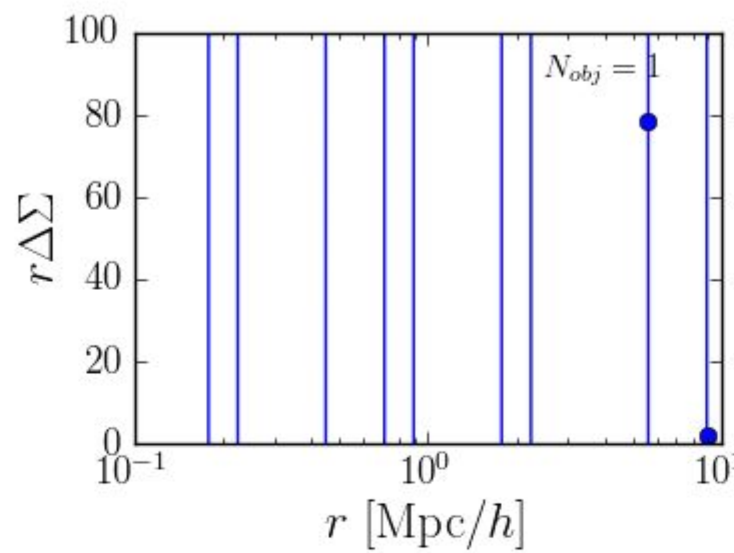
Stacking: pros and cons

Pros:

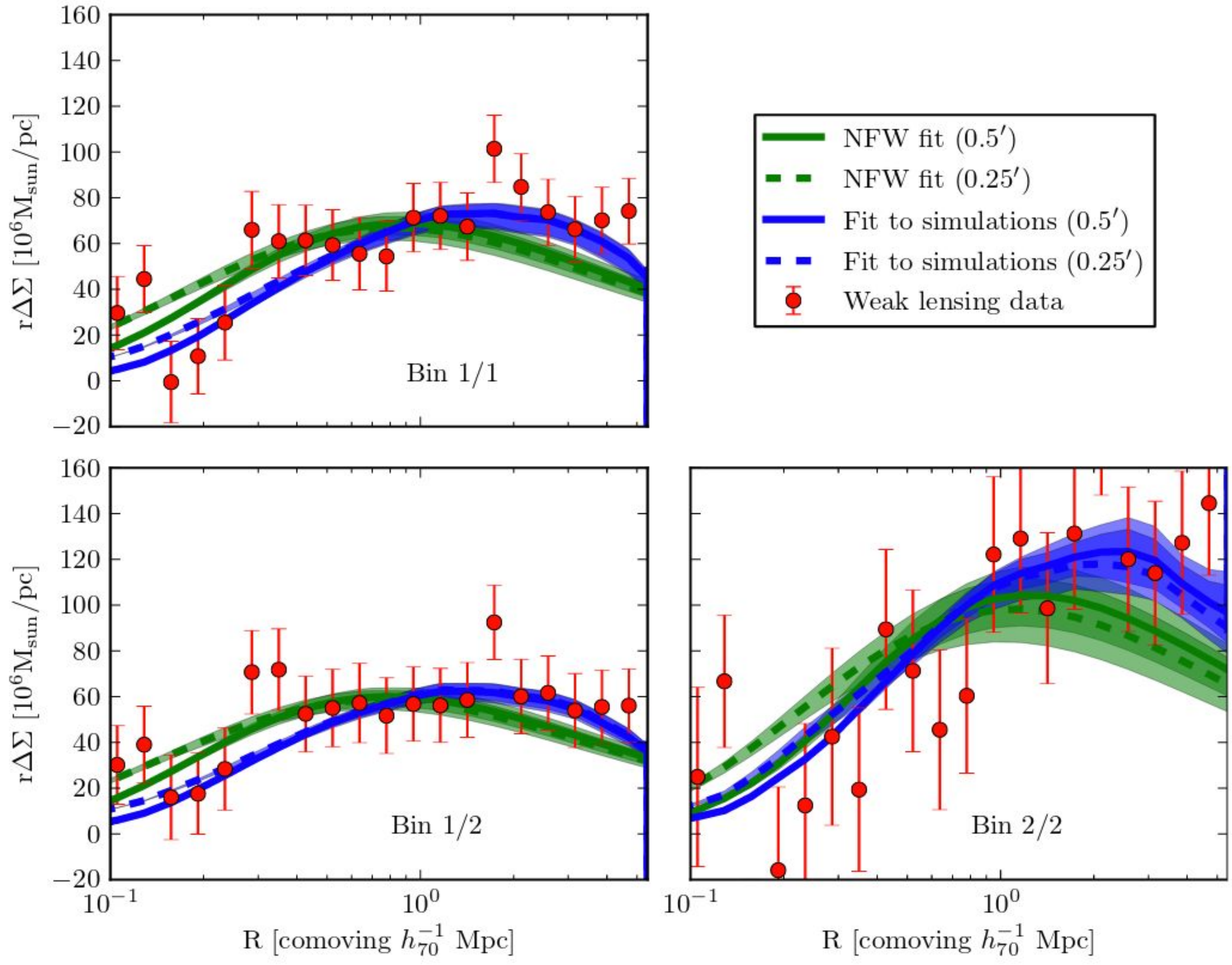
- Can get signal even if each lens is low S/N
- Some pernicious effects average out
- Can statistically correct for, e.g., contamination and centroiding errors

Cons:

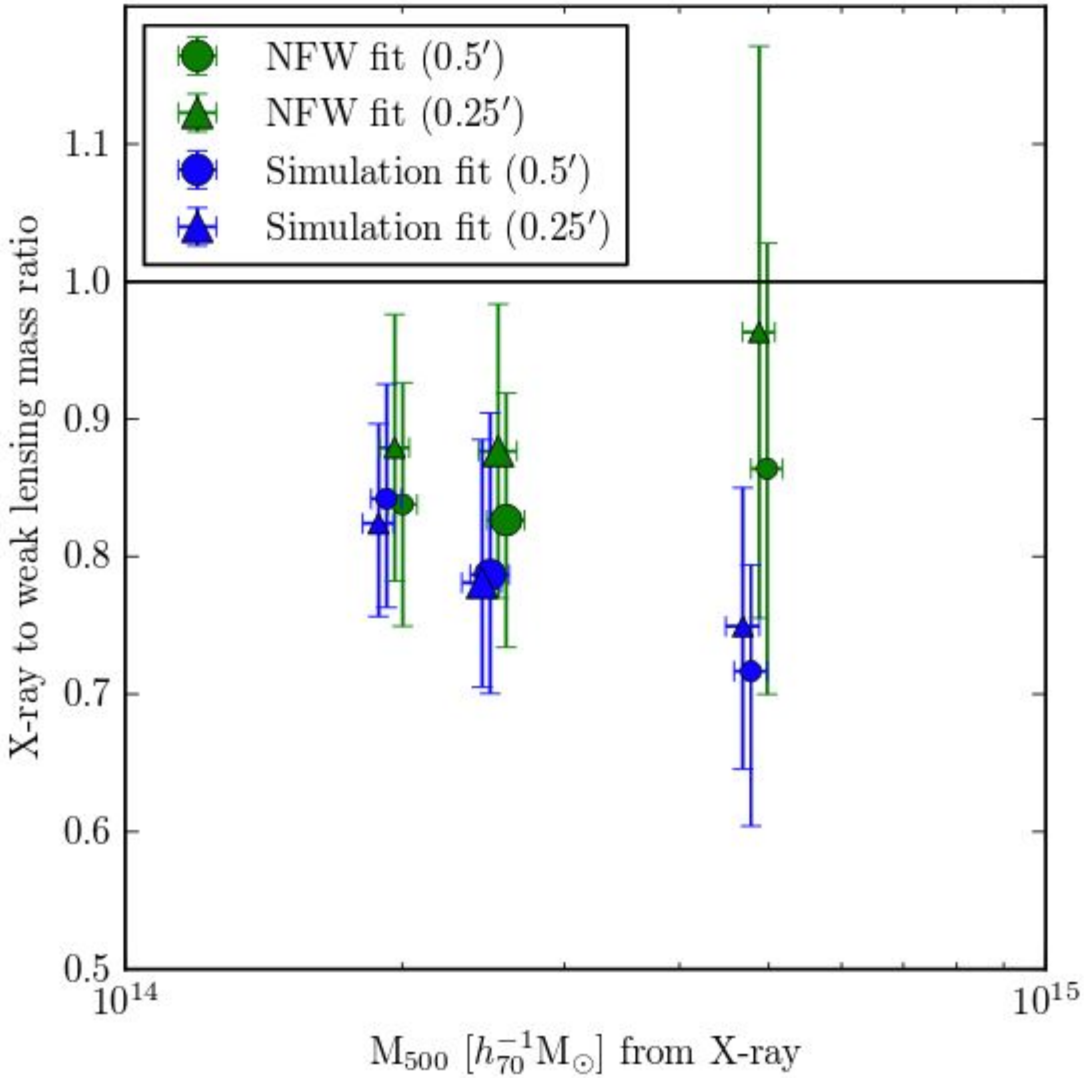
- Loses information
- Harder to compare to outside measurements such as X-ray or SZ
- Can't measure scatter



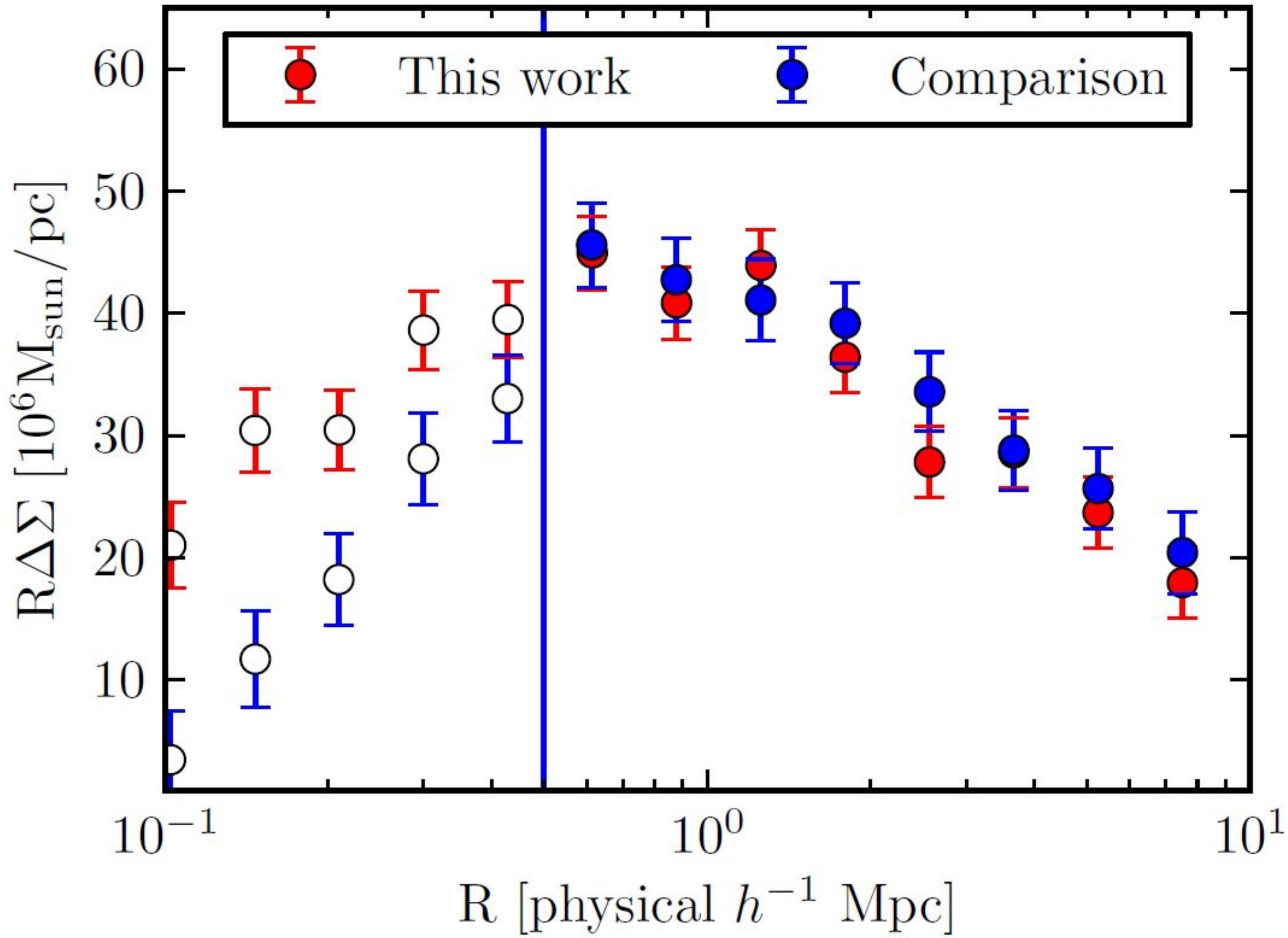
Not much choice for SDSS: we just don't have enough signal-to-noise to avoid stacking.



NFW fit (0.5′)
NFW fit (0.25′)
Fit to simulations (0.5′)
Fit to simulations (0.25′)
Weak lensing data
Bin 1/1
Bin 1/2
Bin 2/2
$r\Delta\Sigma\ [10^6 M_{sun}/pc]$
R [comoving h_{70}^{-1} Mpc]
160
140
120
100
80
60
40
20
0
−20
10^{-1}
10^{0}


NFW fit (0.5′)
NFW fit (0.25′)
Simulation fit (0.5′)
Simulation fit (0.25′)
X-ray to weak lensing mass ratio
1.1
1.0
0.9
0.8
0.7
0.6
0.5
10^{14}
10^{15}
M_{500} [$h_{70}^{-1} M_\odot$] from X-ray

redMaPPer clusters

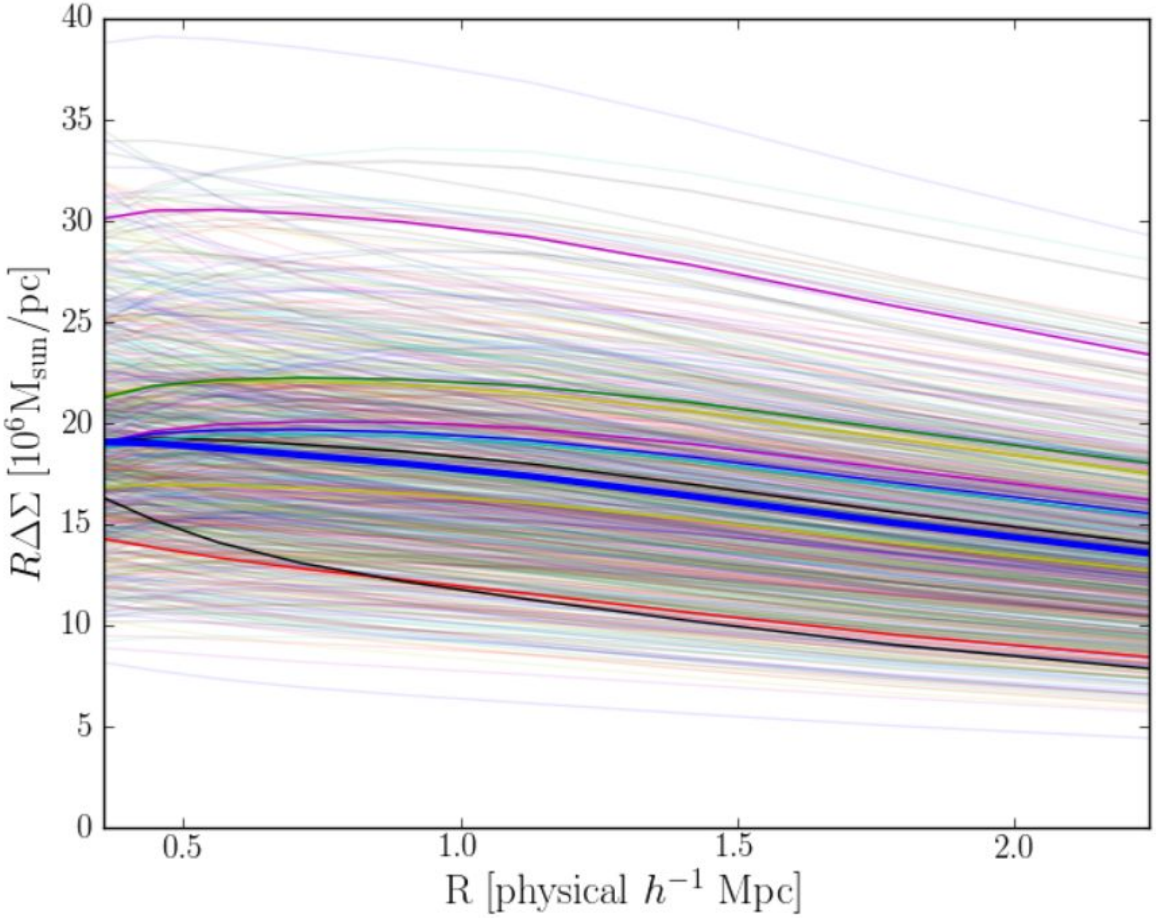


Simet et al 2017, arXiv:1603.06953

Modeling redMaPPer clusters

Interpretation of a stack can be difficult: many objects with different characteristics, averaged.

- Solution: generate a model for the signal that mimics the stacking properties of the data.
- Use NFW haloes as the base and add them using the weights we think they have in the real lensing signal.
- Parameterize with global parameters of interest and fit with an MCMC.
- Per-lens model means it's easy to include systematic effects
- When scatter is needed, do a single random realization--we have enough haloes that this converges.

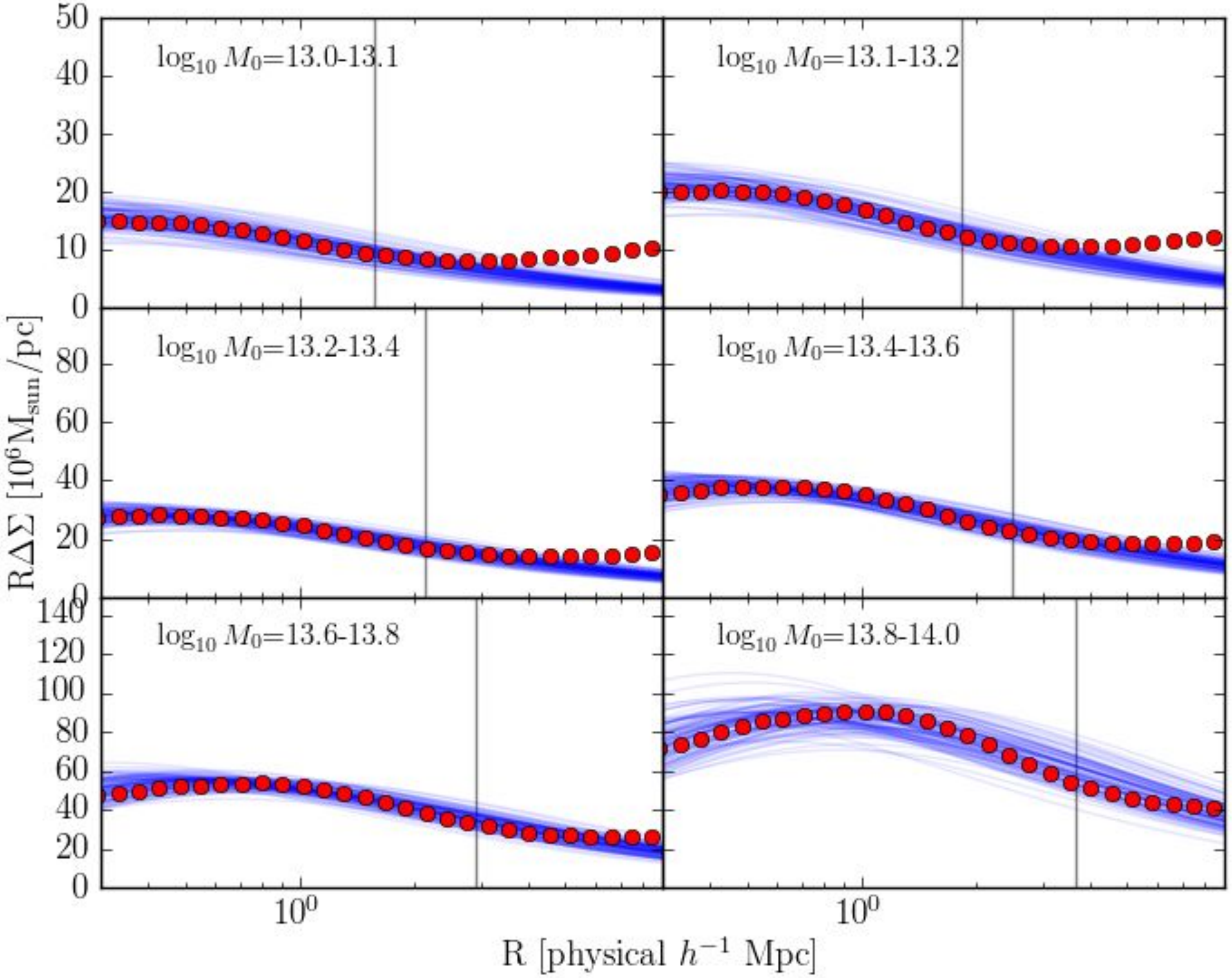


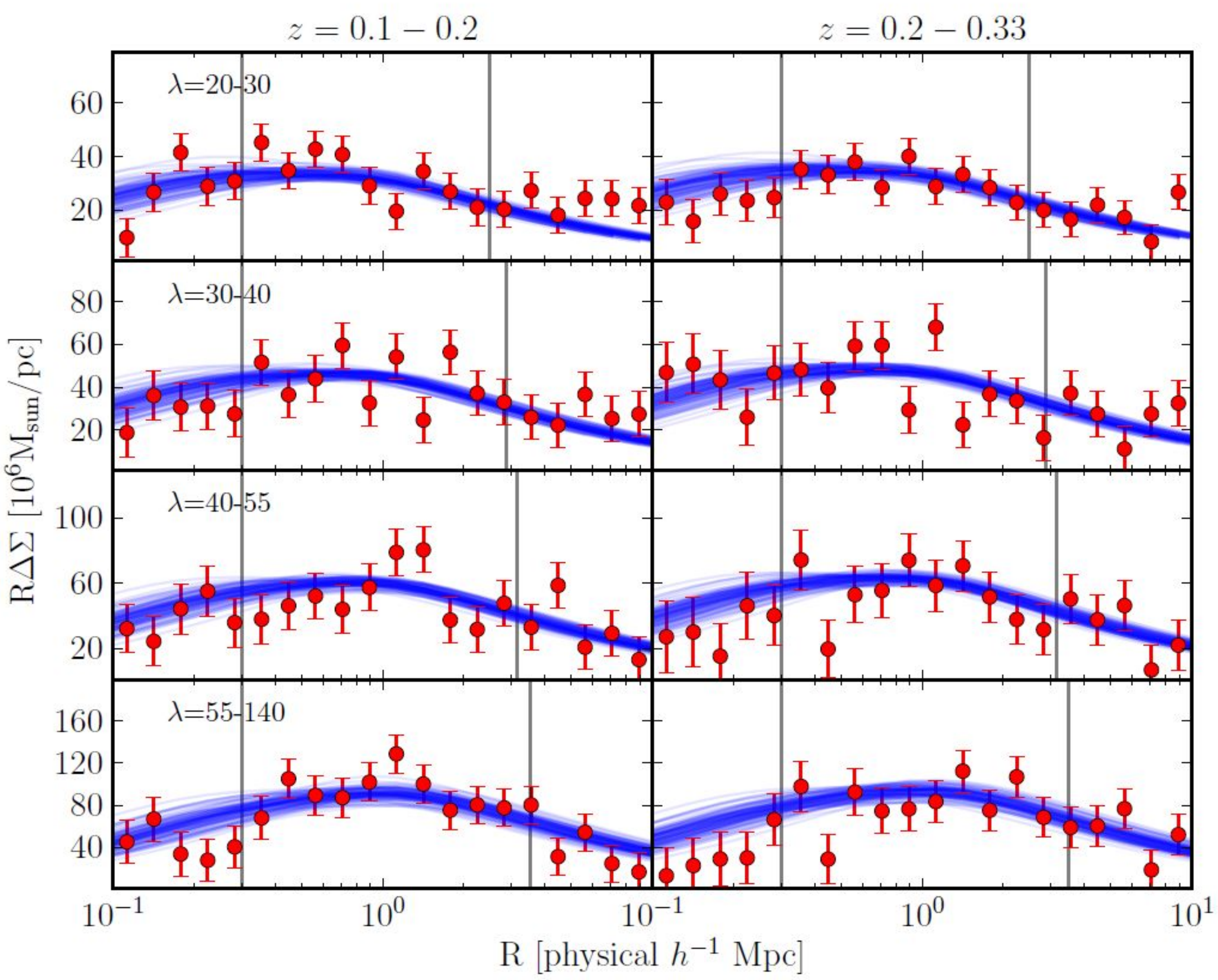
40
35
30
25
20
15
10
5
0
0.5
1.0
1.5
2.0
$R\Delta\Sigma$ [$10^6 \mathrm{M_{sun}}$/pc]
R [physical h^{-1} Mpc]

Sources of systematic error

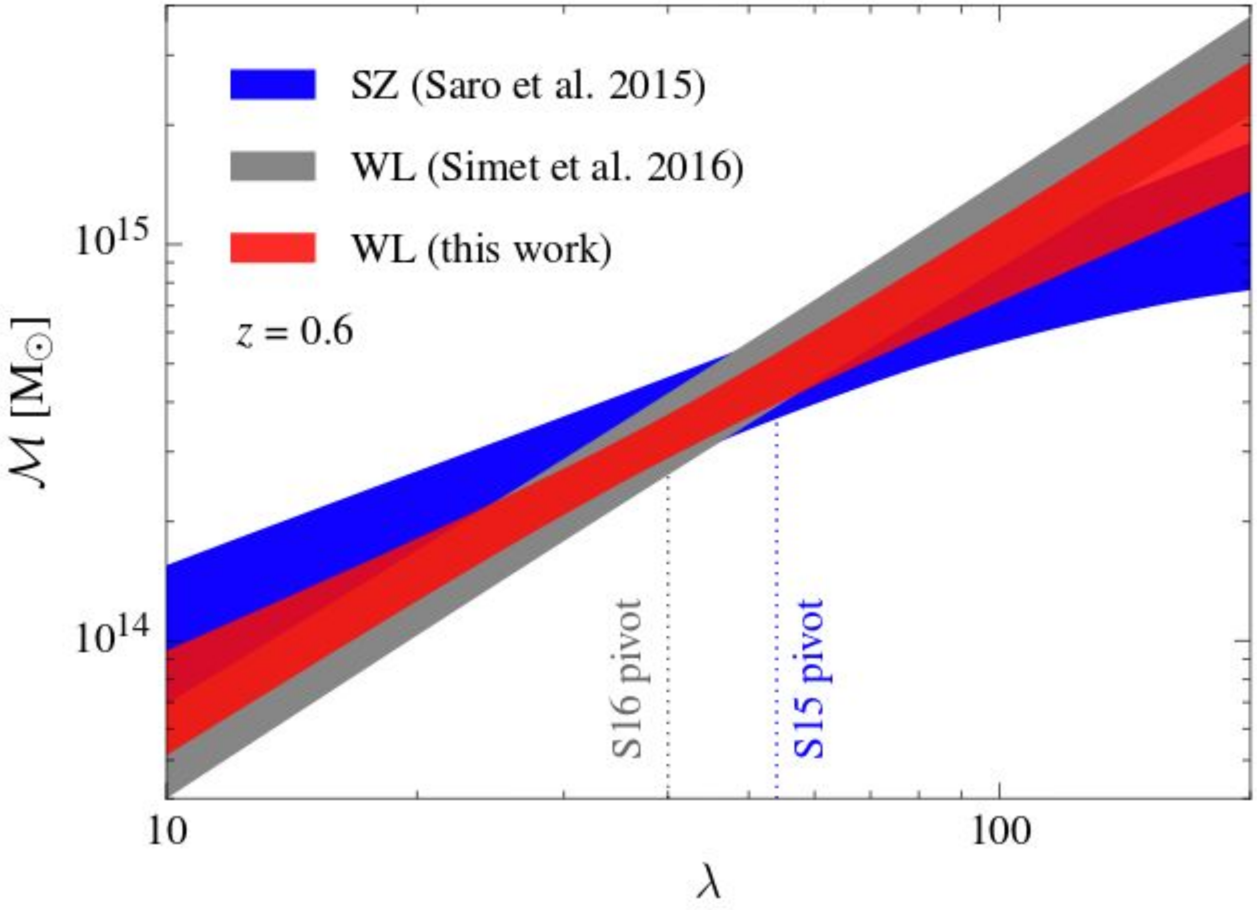
- Problems from the shape and redshift catalog:
  - Shear calibration errors, selection, photo-*z* bias, deblending - size estimated from simulation, measurement & lensing signal comparison
- Problems from physical effects of known size
  - Magnification, obscuration - neither important here
  - Cluster miscentering - priors from other analyses
- Problems from physical effects of unknown size
  - Projection effects - a posteriori correction; ongoing work
  - Intrinsic alignments - almost certainly small
  - Baryonic effects - future work
  - Non-spherical halos - a posteriori correction; ongoing work

Comparison to simulation



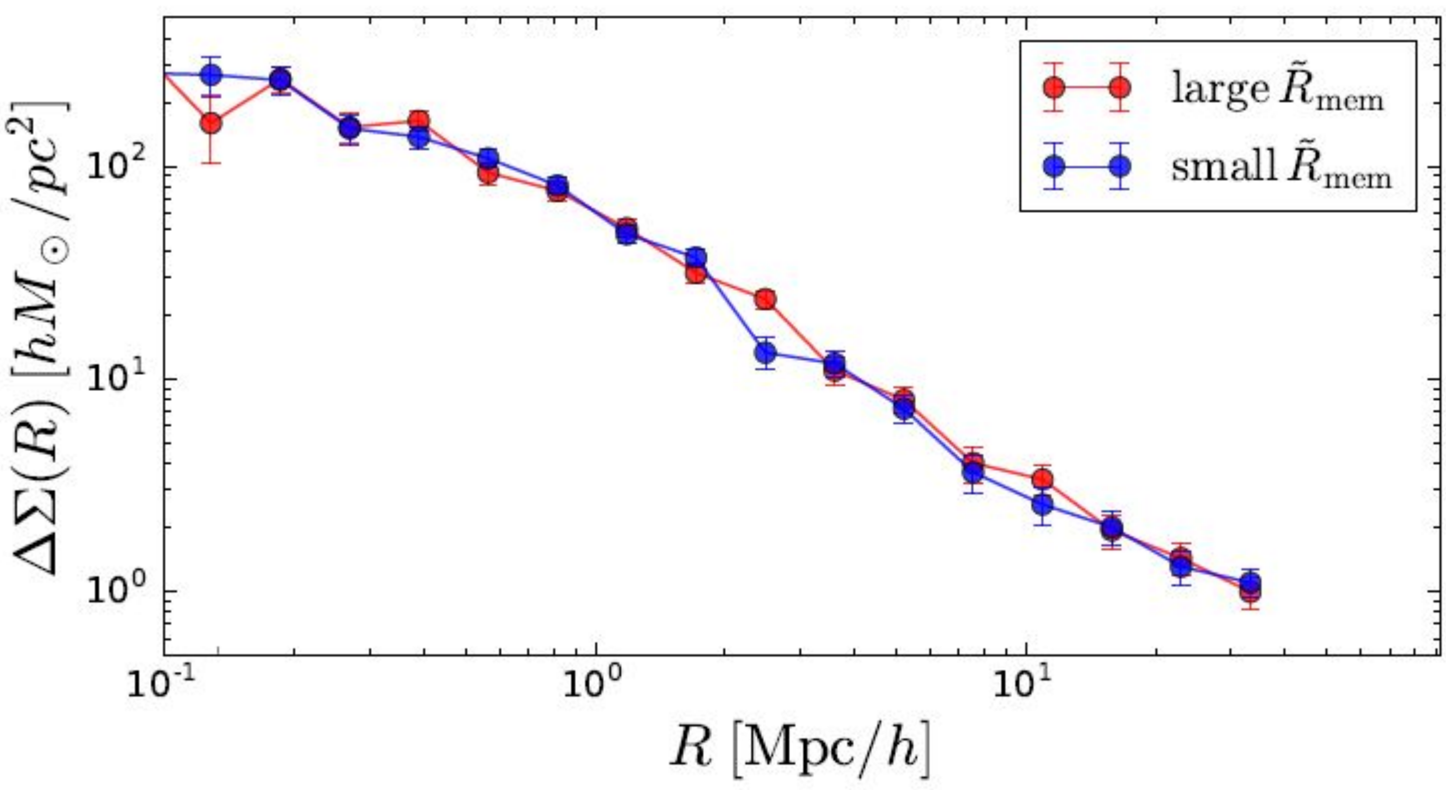


$z = 0.1 - 0.2$
$z = 0.2 - 0.33$
λ=20-30
λ=30-40
λ=40-55
λ=55-140
R$\Delta\Sigma$ [10^6M$_{\rm sun}$/pc]
R [physical h^{-1} Mpc]



Melchior et al. 2016 (DES)

Assembly bias?



Zu et al. 2016, arXiv:1611.00366

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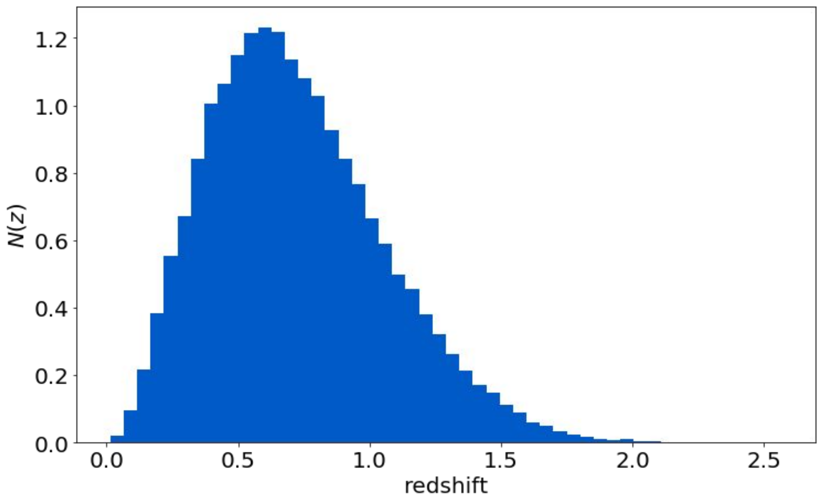
The problem

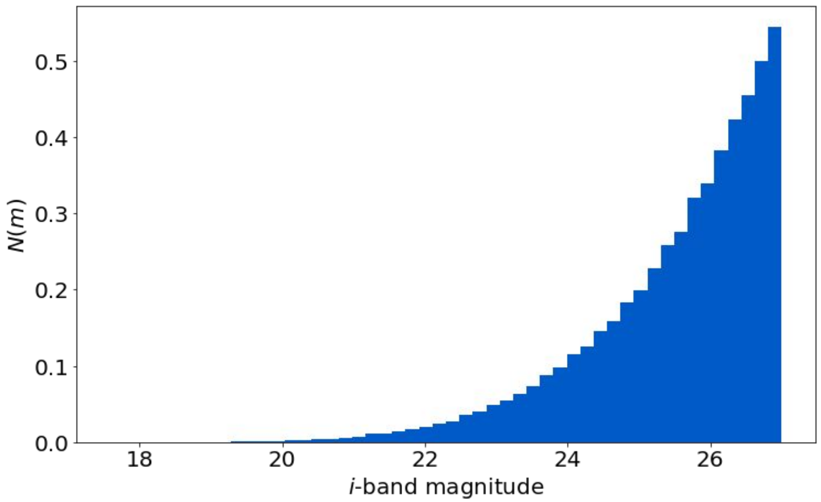
In current and upcoming surveys, many galaxies will be *blended*.

Can we detect previously-undetected galaxy blends using their colors?

Toy-model simulations

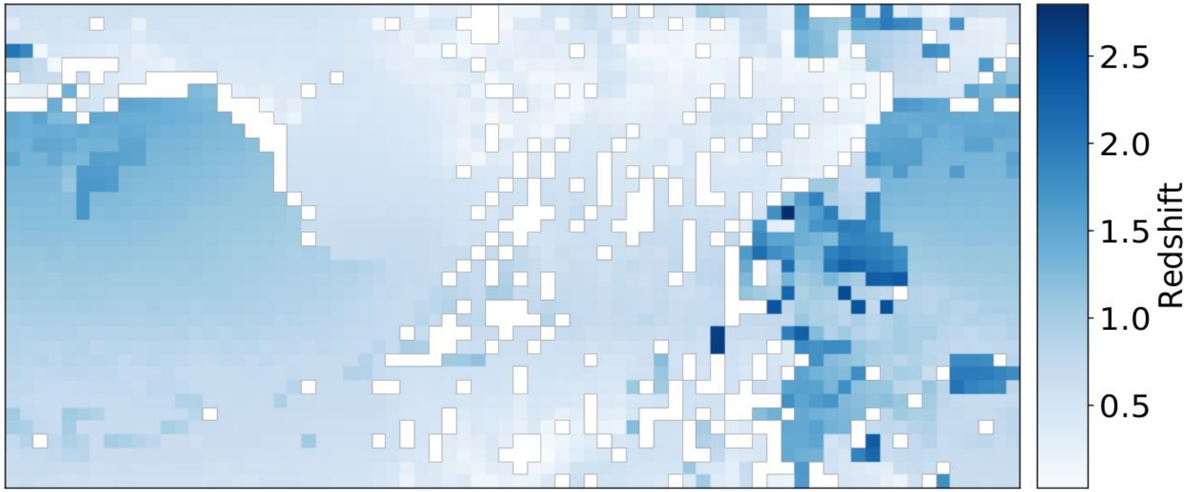
- Randomly draw two numbers from a redshift distribution
- Randomly draw two templates for galaxy spectra (Brown et al 2013)
- Randomly draw two magnitudes
- Redshift the spectra to the right template, get the flux in LSST bands (ugrizy)
- Add the fluxes
    - Note: no extinction in following plots (active work)





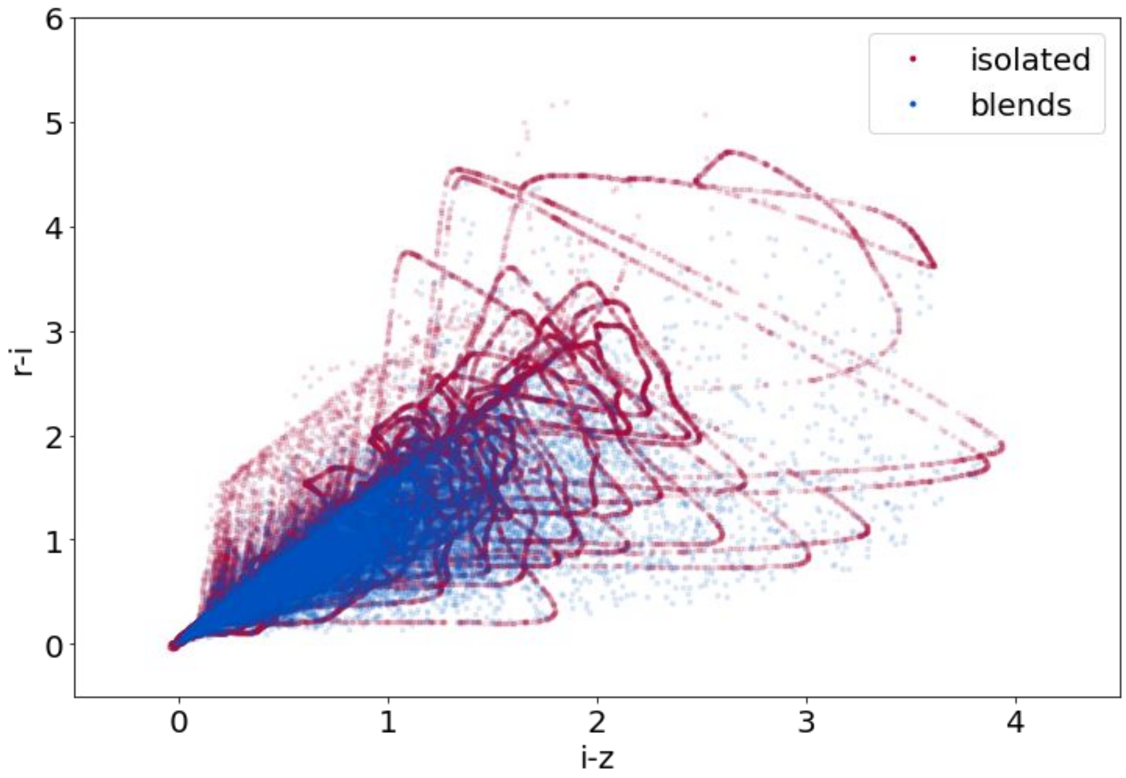
A quick tour of self-organizing maps

A self-organizing map is a 2D representation of a high-dimensional manifold.



See: Geach 2012, Carrasco Kind and Brunner 2014, Masters et al 2015 & refs

First question: do galaxy blends have unique colors?



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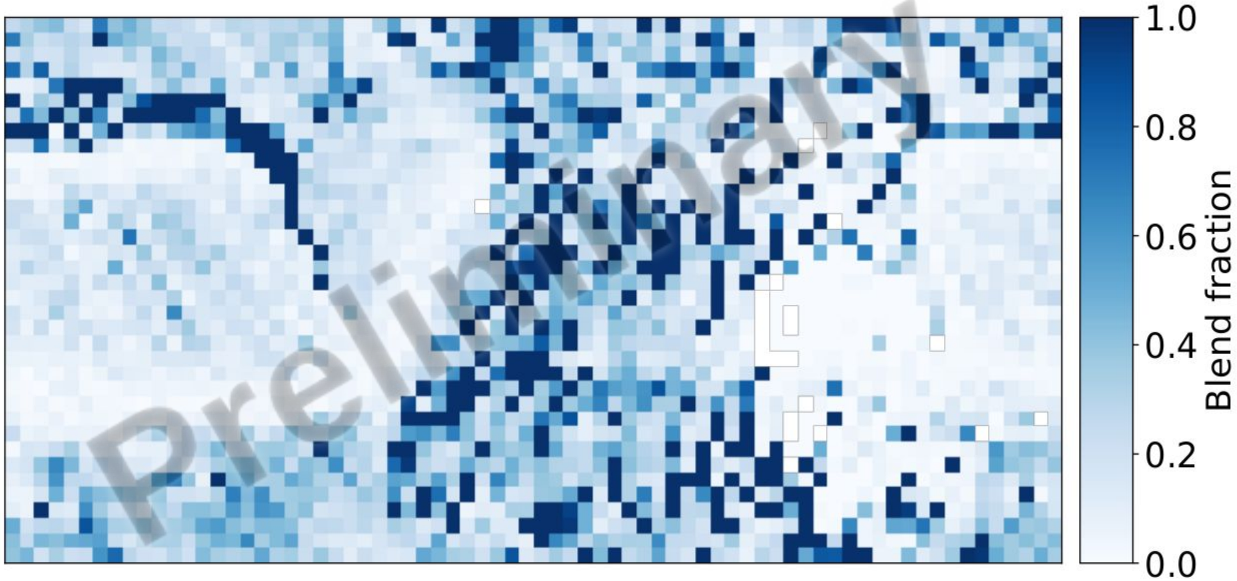
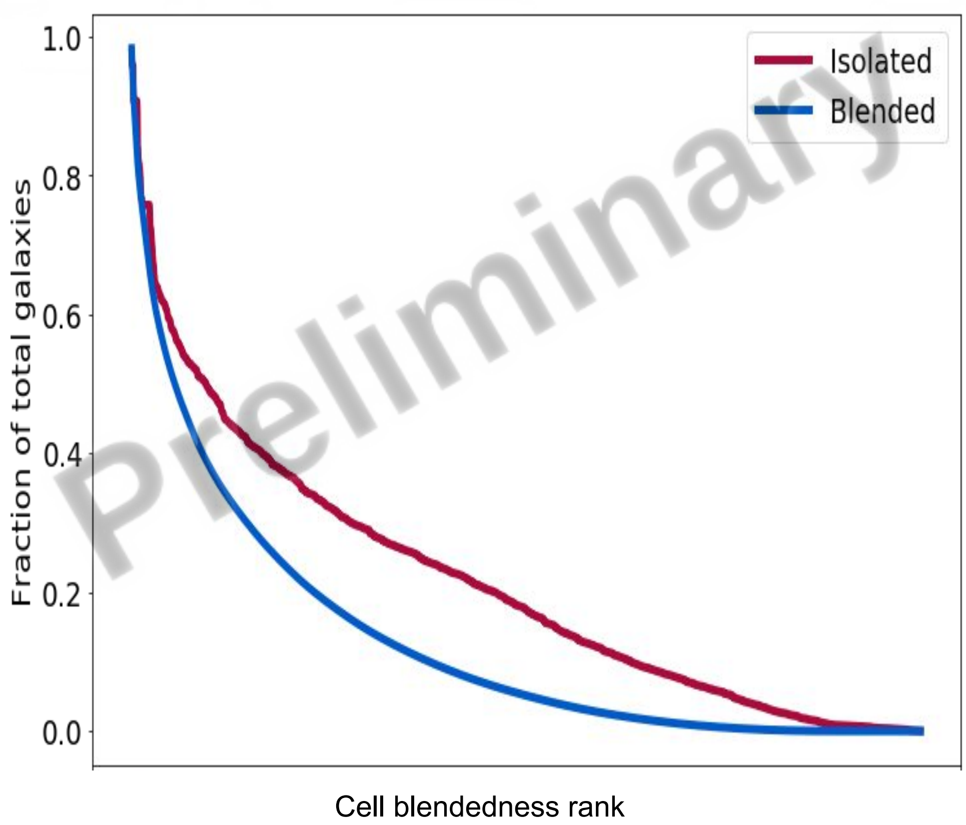


Yes, but...

First question: do galaxy blends have unique colors?

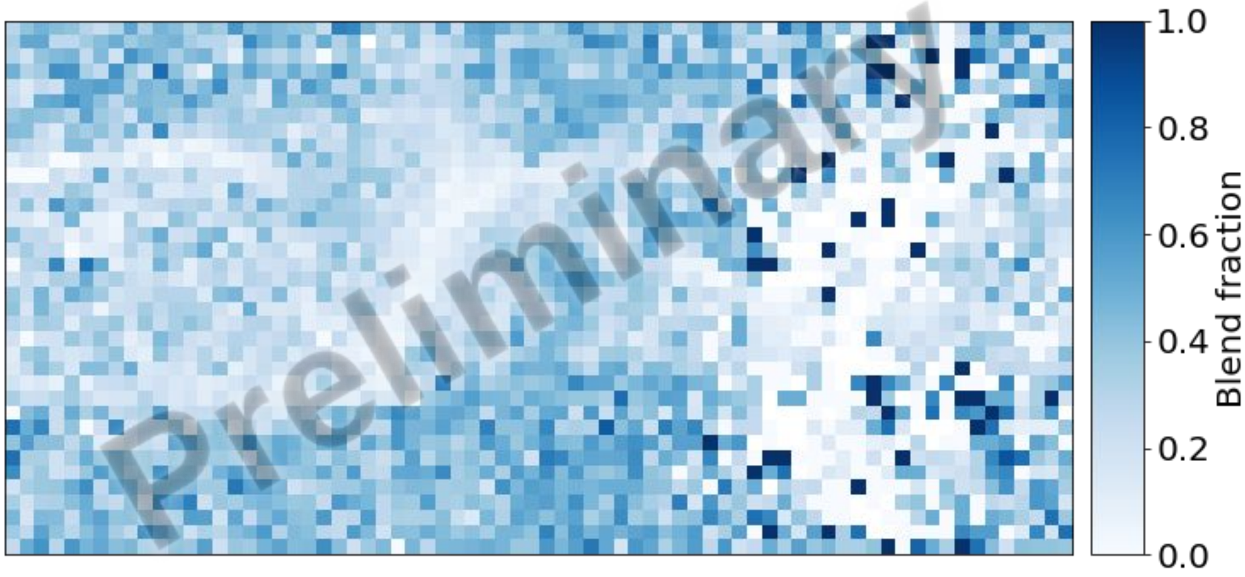
...that was with no photometric noise.

Second question: can we make clean samples?



Depends on fraction of things that are blends, but probably also **no**.

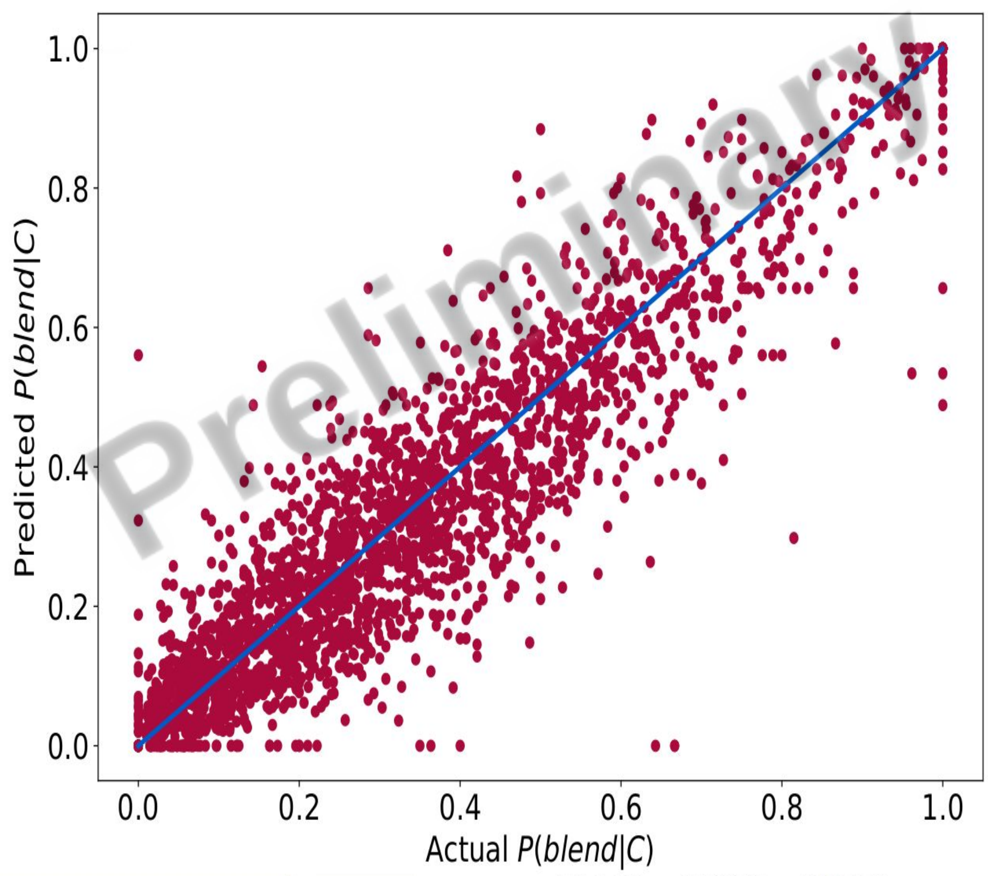
Third question: can we measure the unrecognized blend fraction?



Third question: can we measure the unrecognized blend fraction?

Promising, but noisy...

(As a whole, this predicts 0.323 instead of the expected ⅓))



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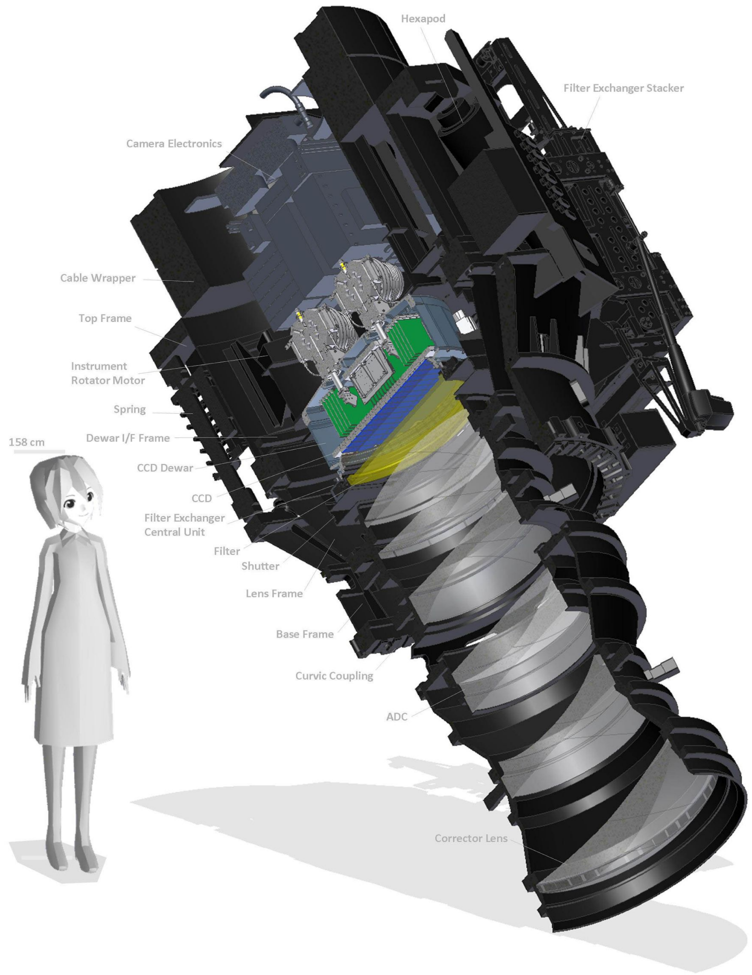
Survey comparison

Survey	PSF FWHM (arcsec)	Area (deg^2)	Source galaxy density (per sq arcmin)	Number of objects
Sloan Digital Sky Survey	1.2	10000	1.1	4.0×10^6
KiloDegree Survey	0.65	1500	12	6.5×10^7
Hyper SuprimeCam	0.6	1500	23	1.2×10^8
Dark Energy Survey	0.9	5000	10	2.0×10^8
WFIRST	0.13	2200	45	3.6×10^8
Euclid	0.13	15000	30	1.6×10^9
Large Synoptic Survey Telescope	0.7	18000	40	2.6×10^9

Hyper SuprimeCam



On the Subaru telescope

1.8 deg^2 FOV

Strategic Survey Program taking place over ~5 years

Currently in year 2

Data products to be made public

Analyzed using the LSST pipeline

No weak lensing results to show you yet (so I'll show some photos)

Magnification

Magnification is a change in observed number density:

$$n_{\rm obs}(\vec{\theta}) = n_0(\vec{\theta})[1 + (2\beta_f + \beta_r - 2)\kappa]$$

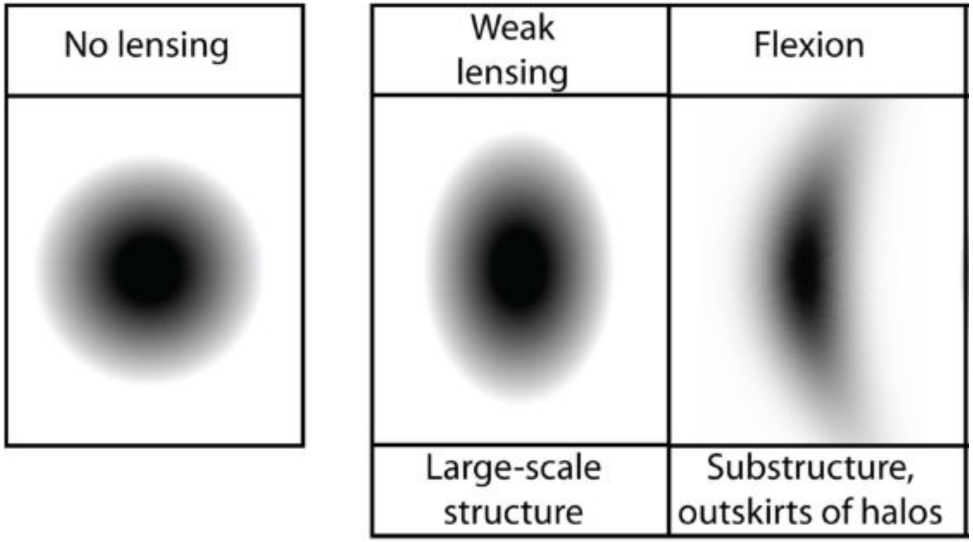
$$\beta_f = -\left.\frac{\partial \ln n_{\rm obs}}{\partial \ln f}\right|_{\substack{f=f_{\rm min}\\ r=r_{\rm min}}}; \quad \beta_r = -\left.\frac{\partial \ln n_{\rm obs}}{\partial \ln r}\right|_{\substack{f=f_{\rm min}\\ r=r_{\rm min}}}$$

Since there are many more small and faint things, deeper surveys & surveys with smaller PSFs will be able to measure this effect more easily.

Schmidt et al. 2009

Flexion

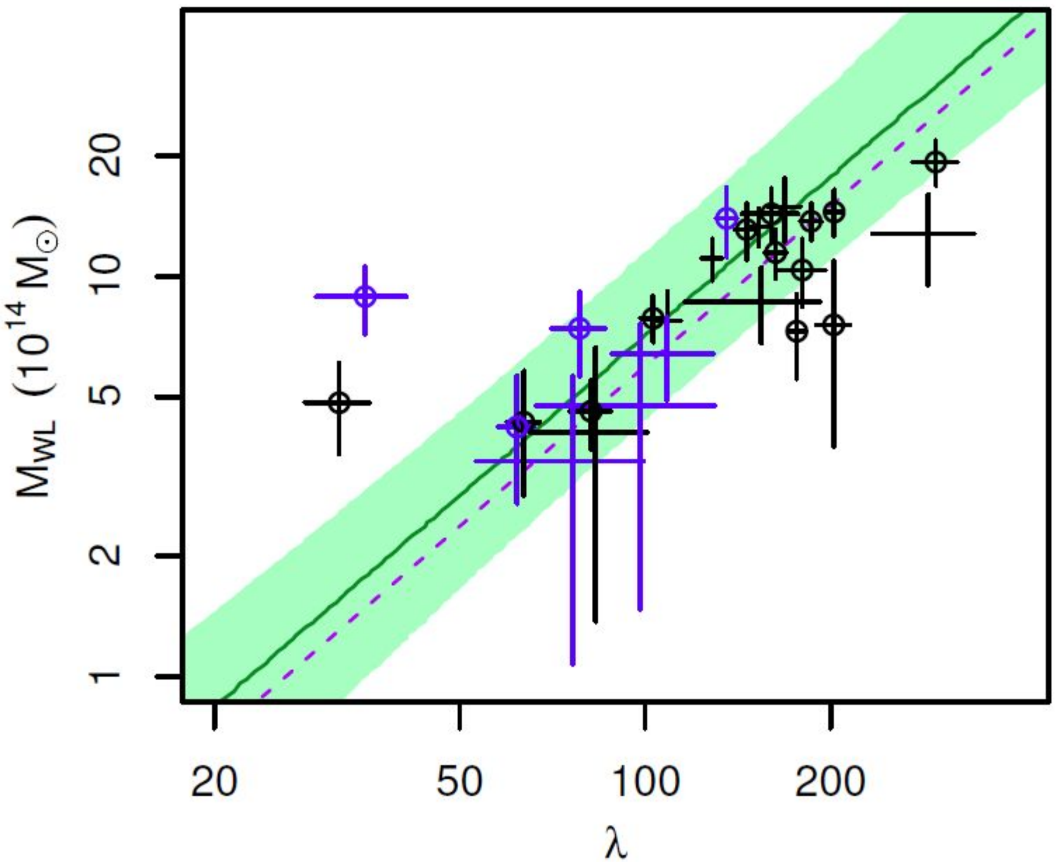
Weak lensing shear is similar to one term in a Taylor expansion of the lensing effect. The next higher term is flexion, or "bananeness".



↦ Harder to measure than shear, but with higher-quality data, maybe!

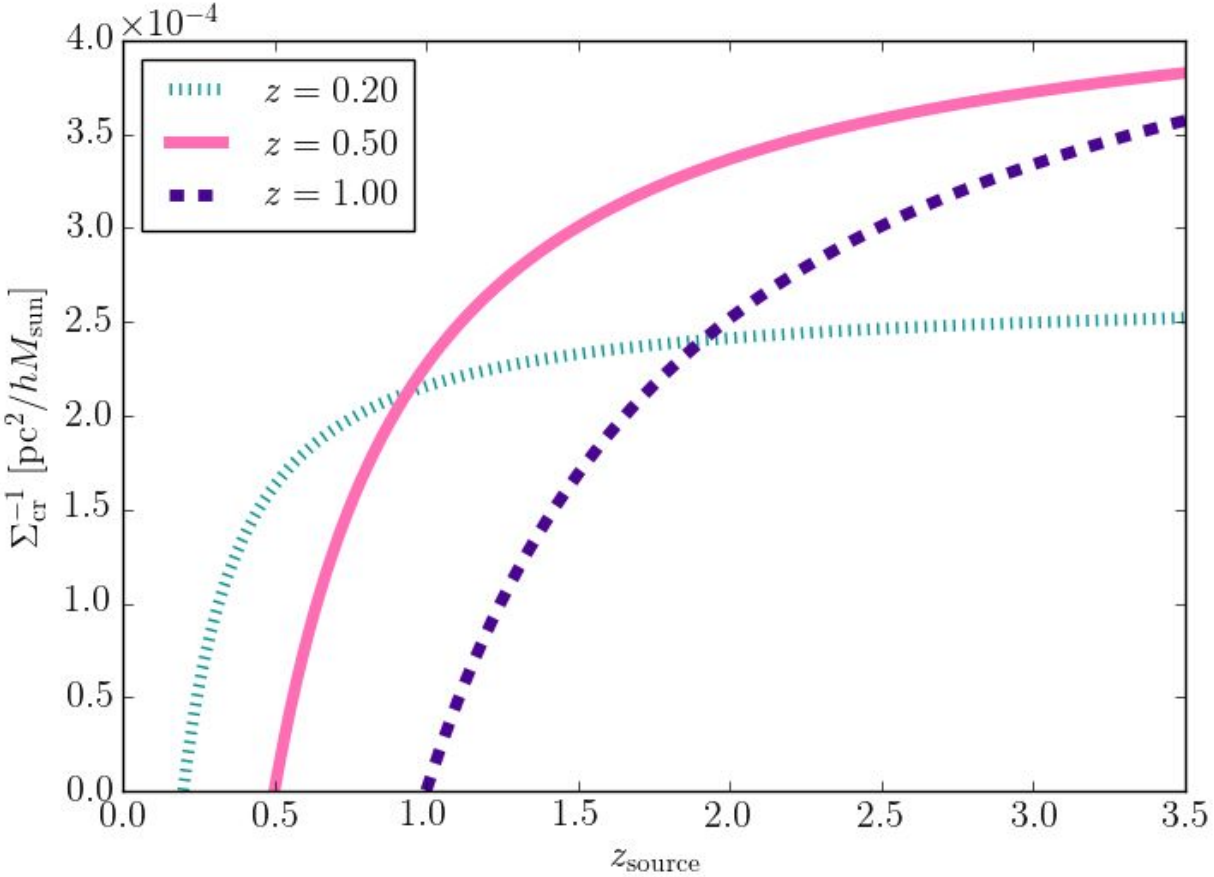
Massey et al. 2010

Per-cluster information



Mantz et al. 2016 arXiv:1606.03407

Tomography (lensing as a function of redshift)



Summary

- We can already make good measurements of many kinds of gravitational lenses & of cosmic shear
- Lots of work still to do in software and modeling
- Some scary systematics, but we're working on them
- Lots of exciting possibilities with upcoming surveys!

What's coming up in the future?

- Mass-concentration for redMaPPer
- Cosmology from the existing mass calibrations
- New missions: HSC, DES, LSST, Euclid, WFIRST...
- Tomography: making measurements in different redshift slices
- New probes of lensing: magnification, flexion, ...
- Per-cluster information on many more clusters
- And more!